LAT Analysis with ScienceTools

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Goals of analysis

- Test for presence of a source, measure its position in the sky
- Extract fluxes of sources of interest. Measure flux vs. time (“lightcurve”) to test for variability.
- Measure spectra of sources
  - Parameters of fitted spectral type, e.g. index of power-law, energy of expenential cut-off, or “super”-exponential cutoff (pulsars)
  - Flux as function of energy (“flux in bands”)

Last time we saw...

- Maximum likelihood is framework/cookbook for estimation and hypothesis testing
- To use, must produce accurate model of data (the rest is derived by following the cookbook)
- Some portions of model are of interest to us
- Others are not
  - Background sources
  - Observational response
- Must be mindful of systematic errors

ScienceTools

- MLE and hypothesis testing is implemented for Fermi LAT data using ScienceTools.
- Data selection and binning into channels.
- Assists in producing of high-level sky model consisting of gamma-ray sources.
- Transformation into low-level Poisson model for each channel (observational response).
- Estimation of parameters through optimization ("minimization") using log-likelihood.
- Calculation of upper limits.

Data exploration

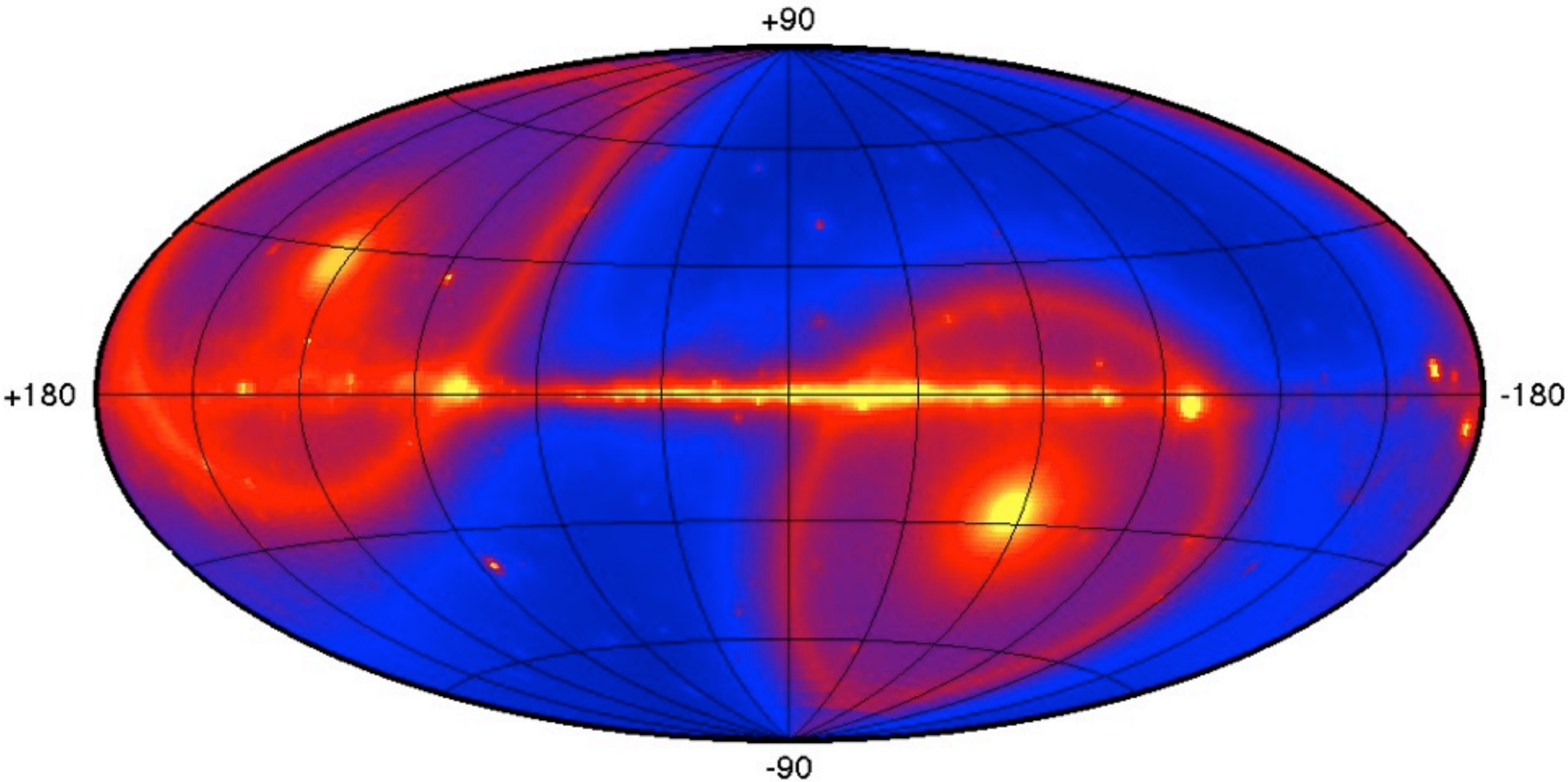
- FT1 files - list of events in FITS format

  Browser: http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

  All-sky: http://heasarc.gsfc.nasa.gov/FTP/fermi/data/lat/weekly/p7v6/

- Events reconstructed @SLAC and consist of:
  - Estimate of direction of origin
  - Estimate of the energy
  - “Probability” of being gamma ray (event classification)
  - Zenith angle, conversion point (front or back), detection time, ...

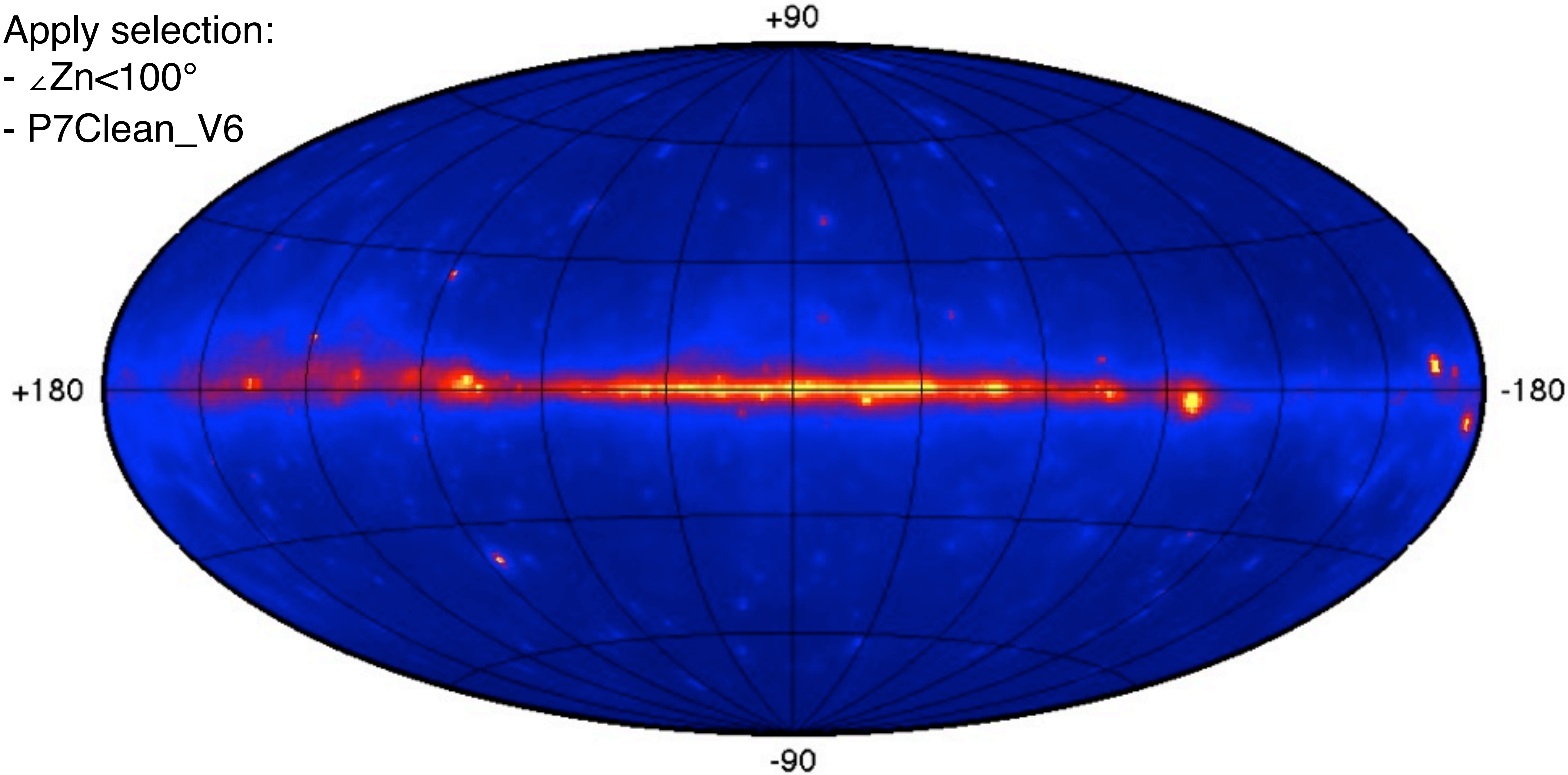
Data set (4.8 years)



- Data set that we would like to analyze (using ML).
- Or in fact, it is a simplification.. the energy and time dependence is not shown!

Data set with sensible cuts

Apply selection:
- ∠Zn<100°
- P7Clean_V6



- Some part of the “background” can be removed: “cuts”.
- Makes it easier to model (remaining) data.
- Rest cannot easily be separated: must be modeled.

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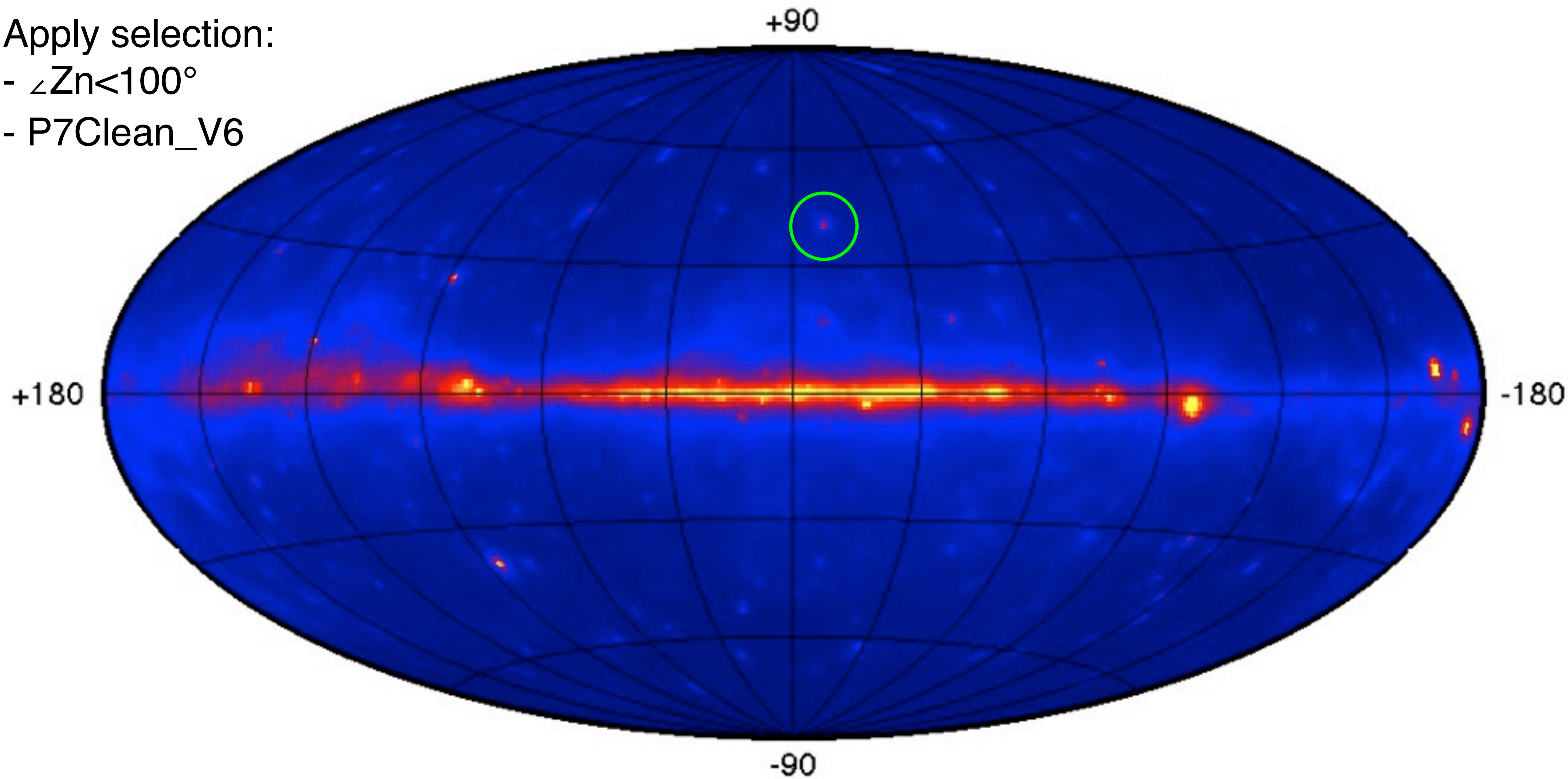

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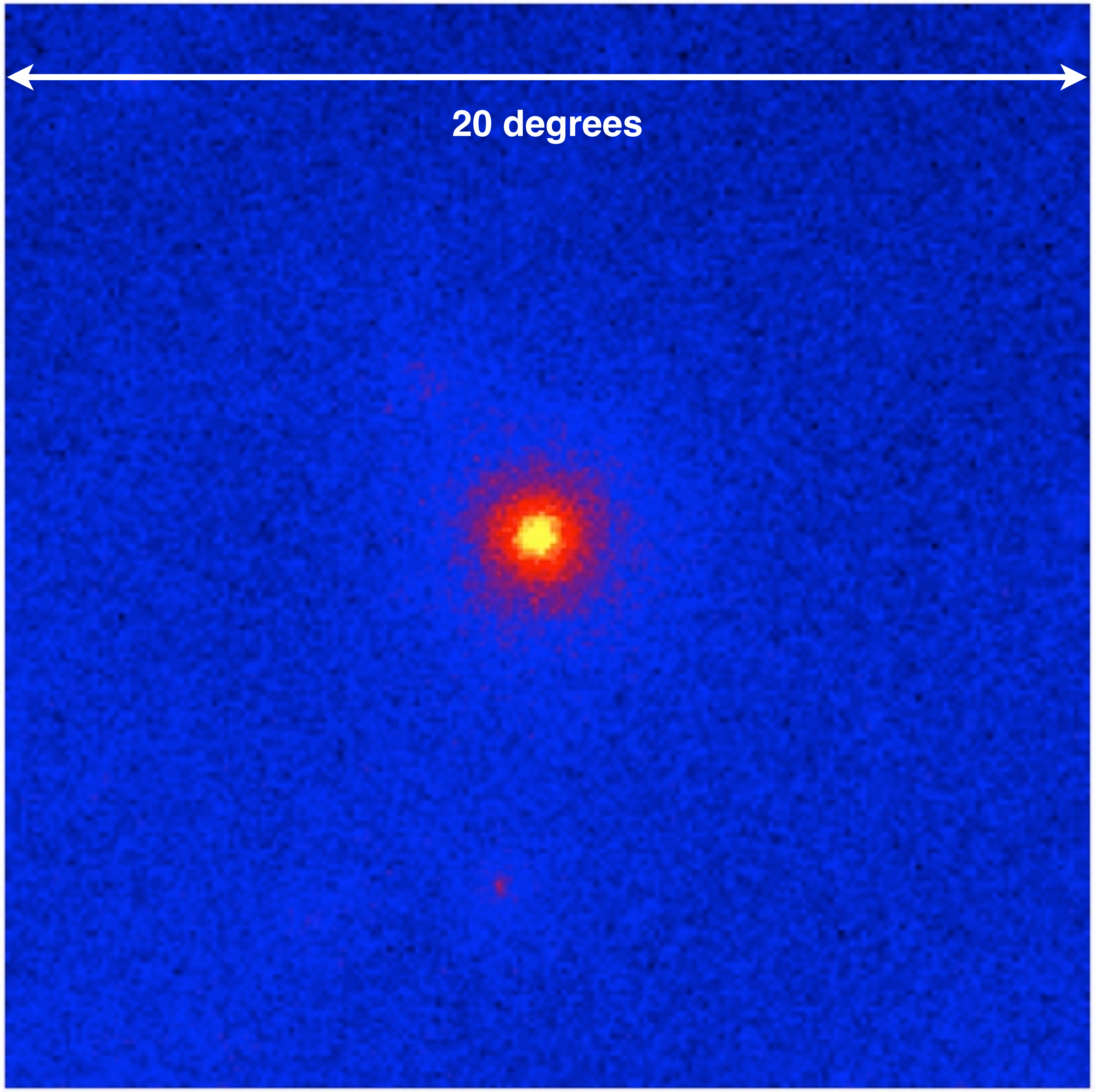
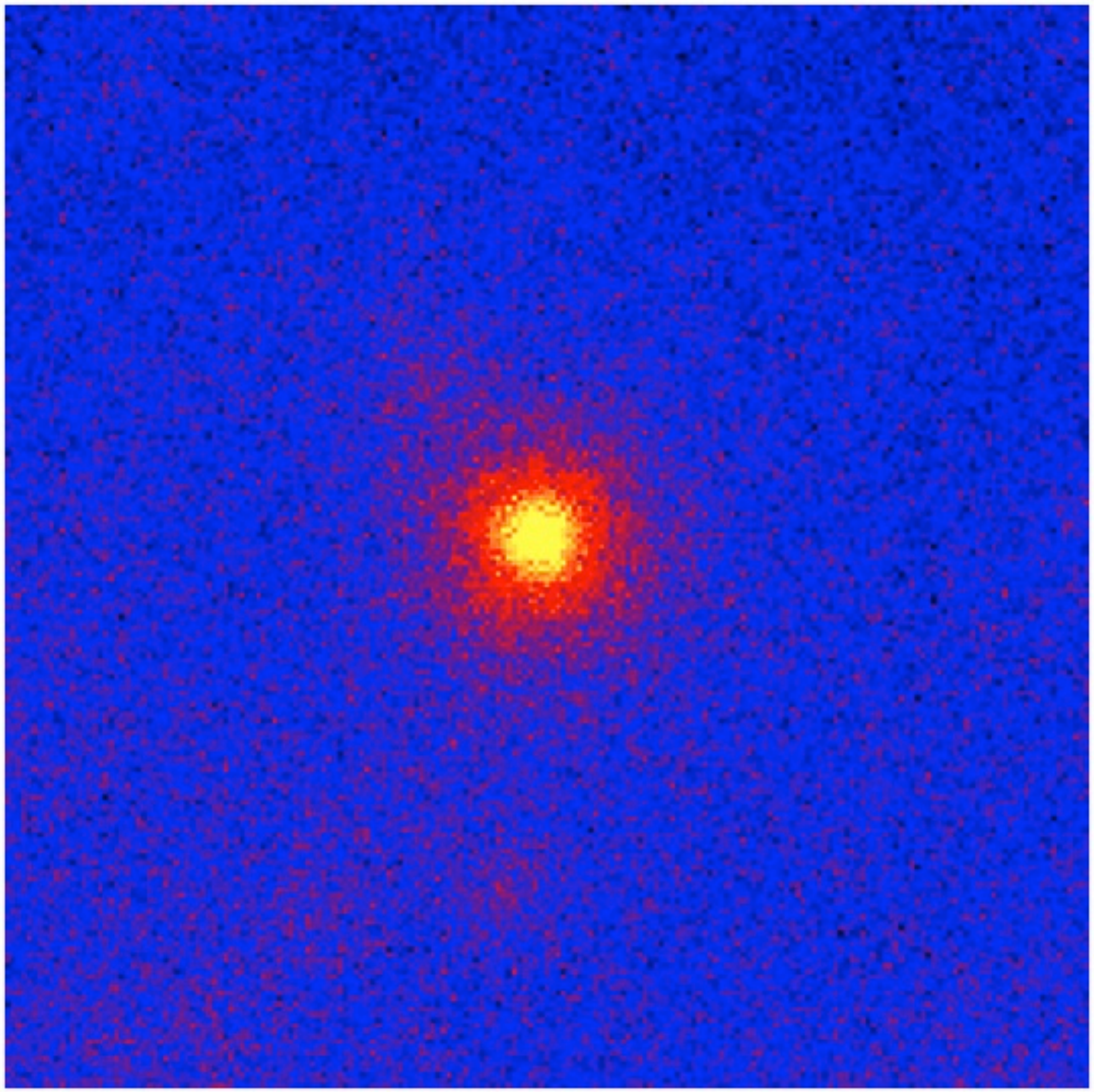
Region of interest (ROI)



0.1GeV - 100GeV

- Don't have to analyze full sky at once!
- Region of interest (ROI) around source.
- Larger: better measure background (>TS)
- Smaller: faster & lower background subtraction systematics (maybe!)
- About 20 degrees is good compromise.

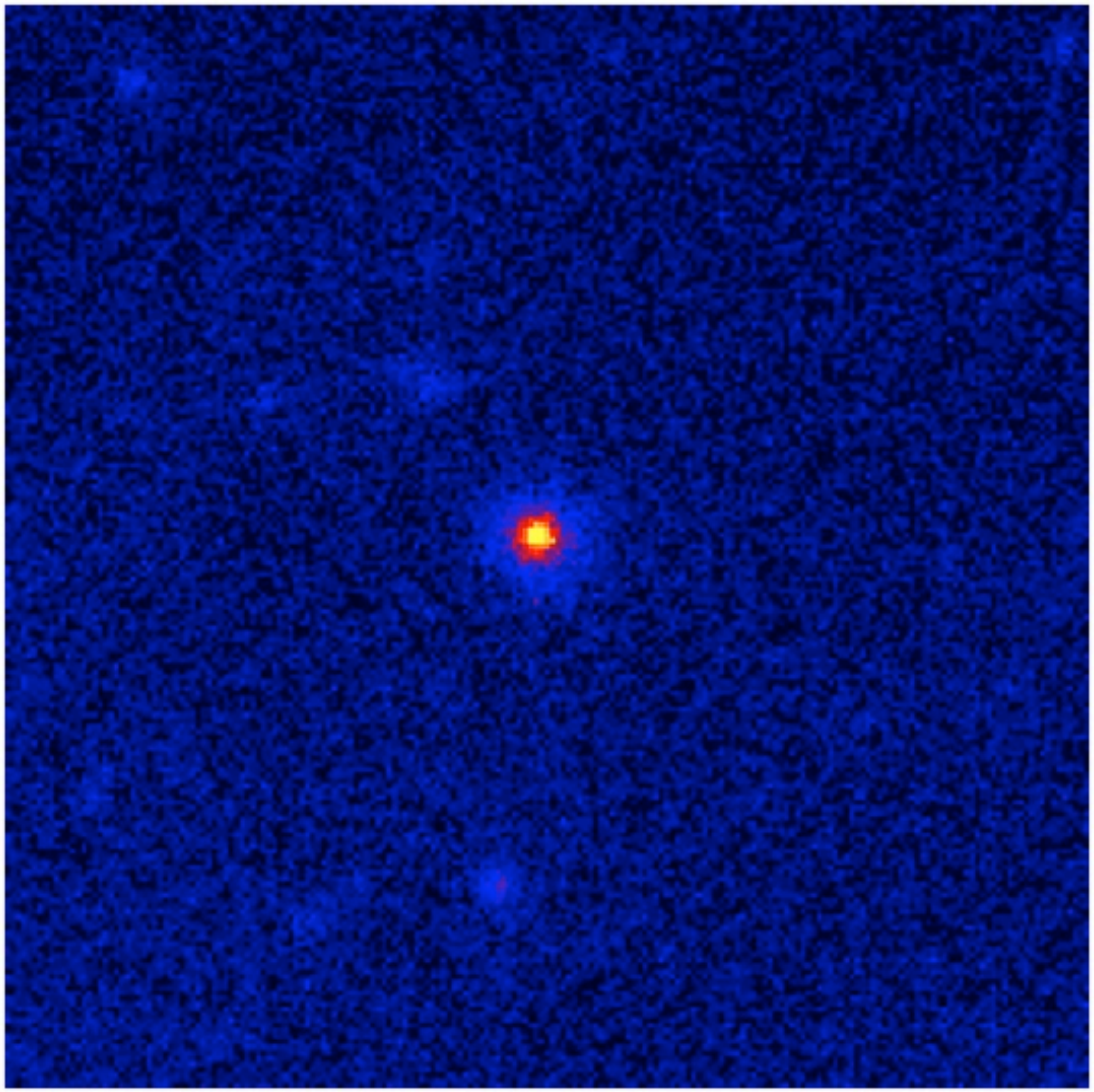
Channels of position & energy



0.1GeV - 1GeV

- Analyze events in channels of position and energy...
- ... as we are interested in spatial and energy dependence of sources
- ... best sensitivity achieved by using all information possible (as long as it can be modeled accurately!)

Channels of position & energy



1GeV - 10GeV

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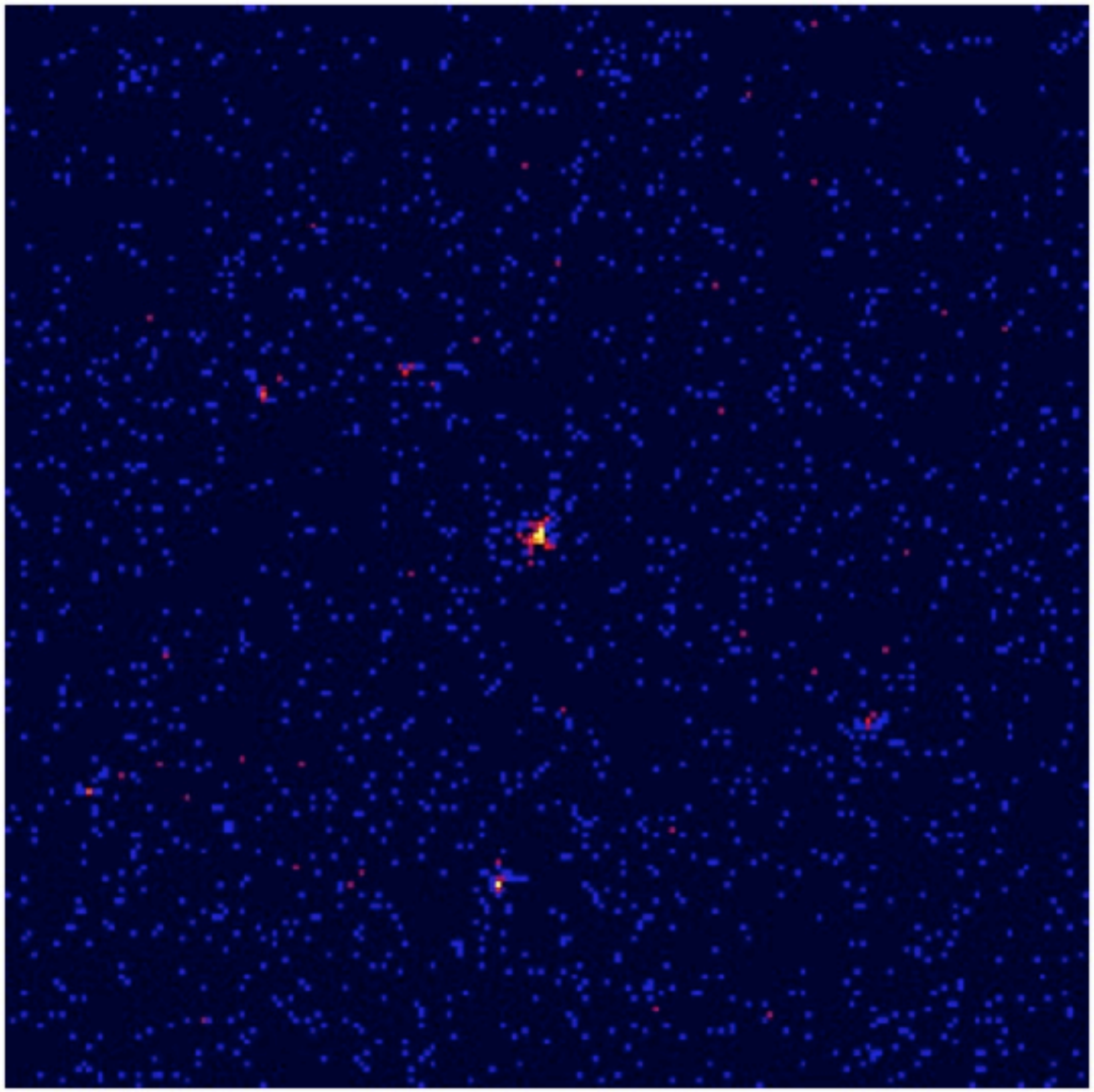

10GeV - 100GeV

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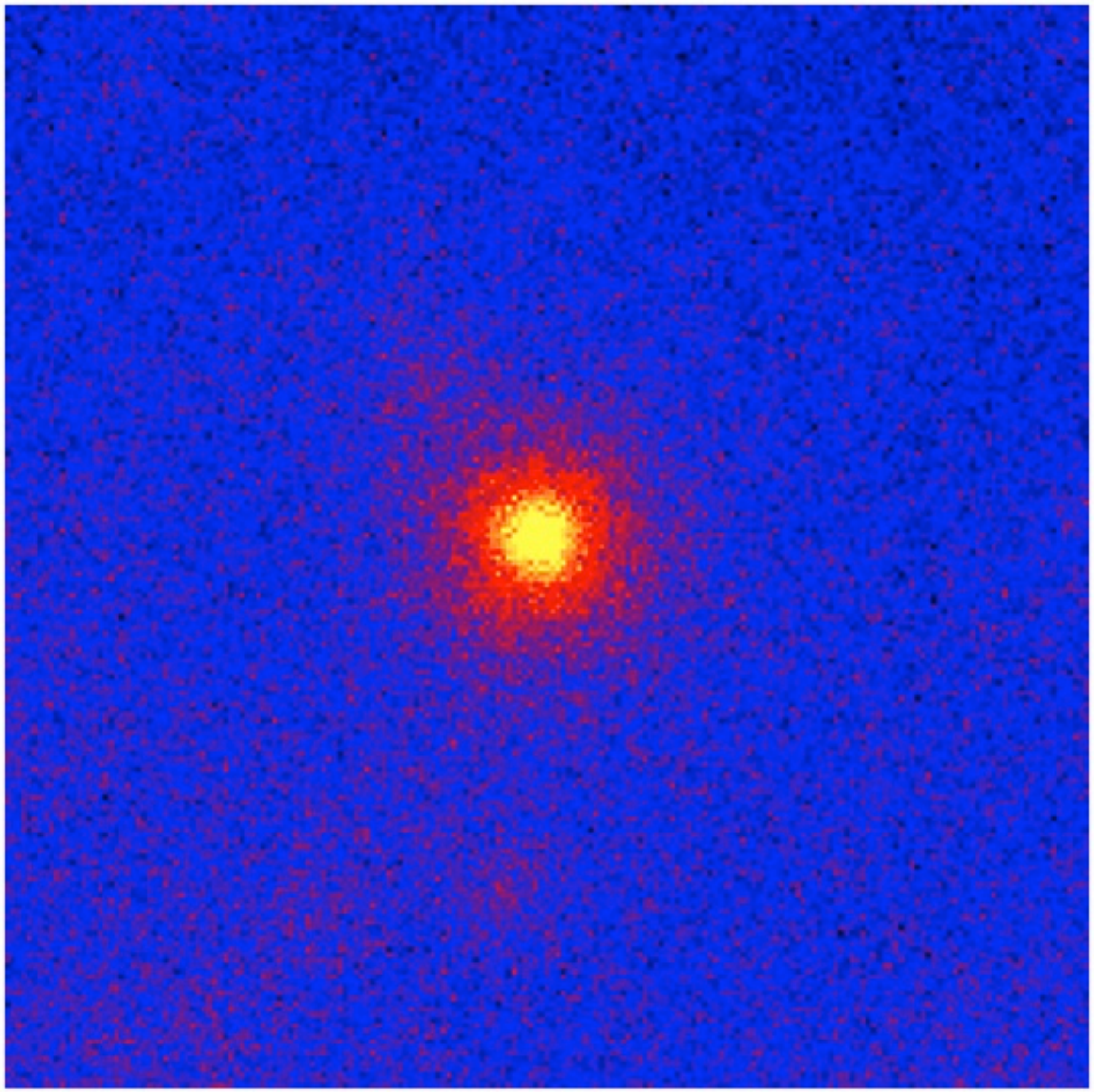
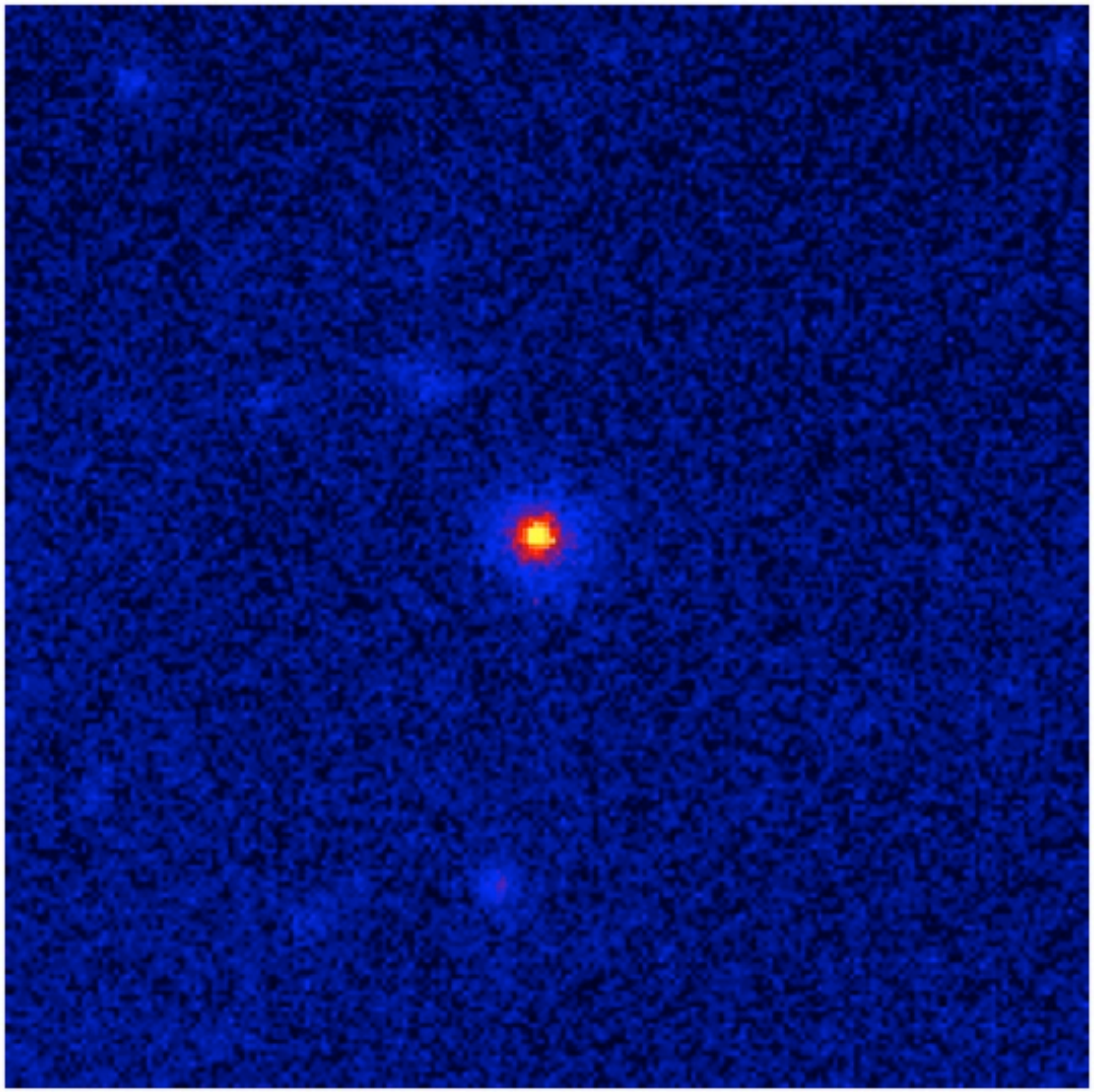
Energy dependency



0.1GeV - 1GeV

1. At higher energies there are fewer events,
2. but, sources look less spread out (PSF)
3. and there is less background.
4. Sources seem most clearly detectable somewhere in the middle range.

Energy dependency



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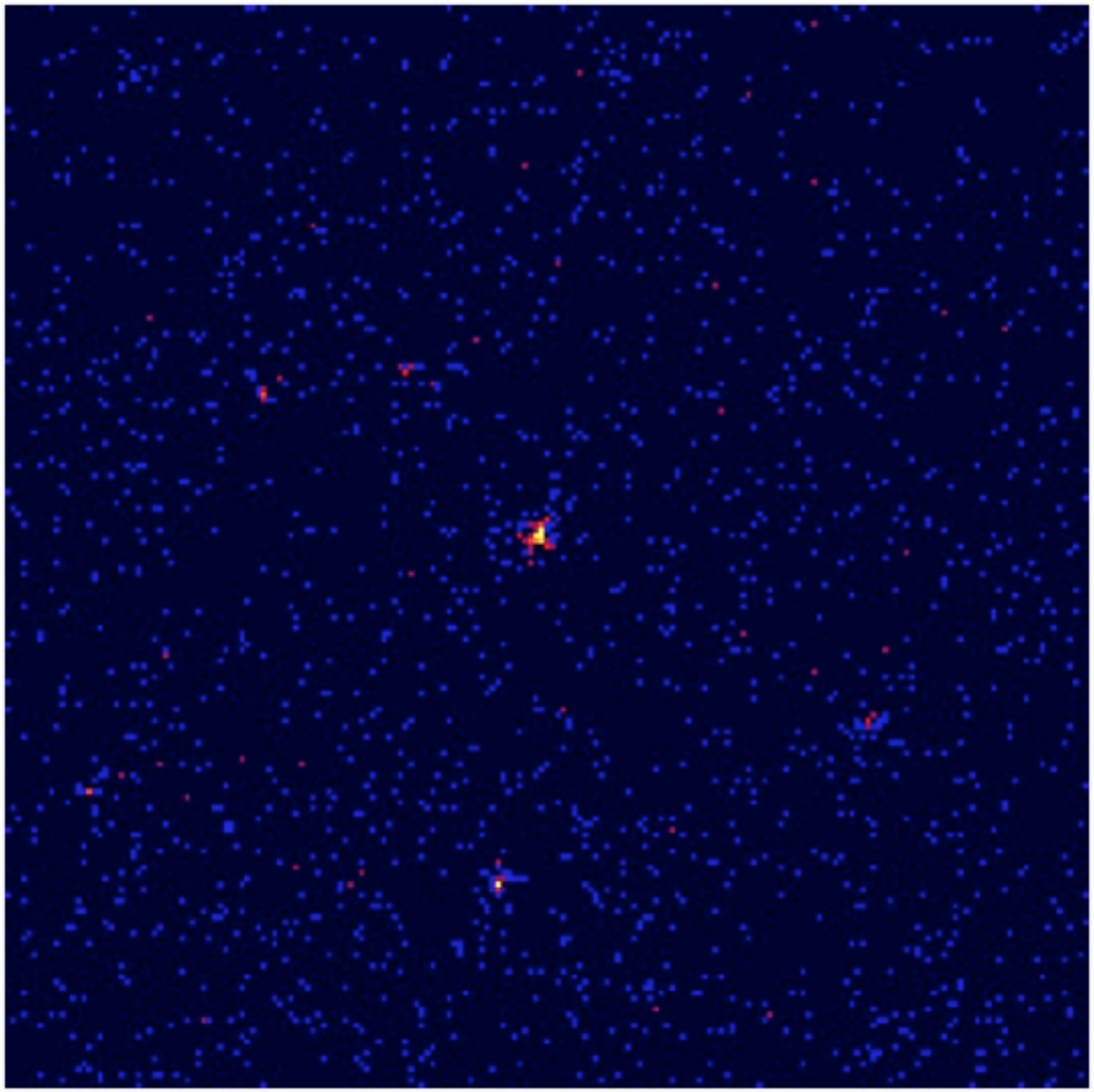

10GeV - 100GeV

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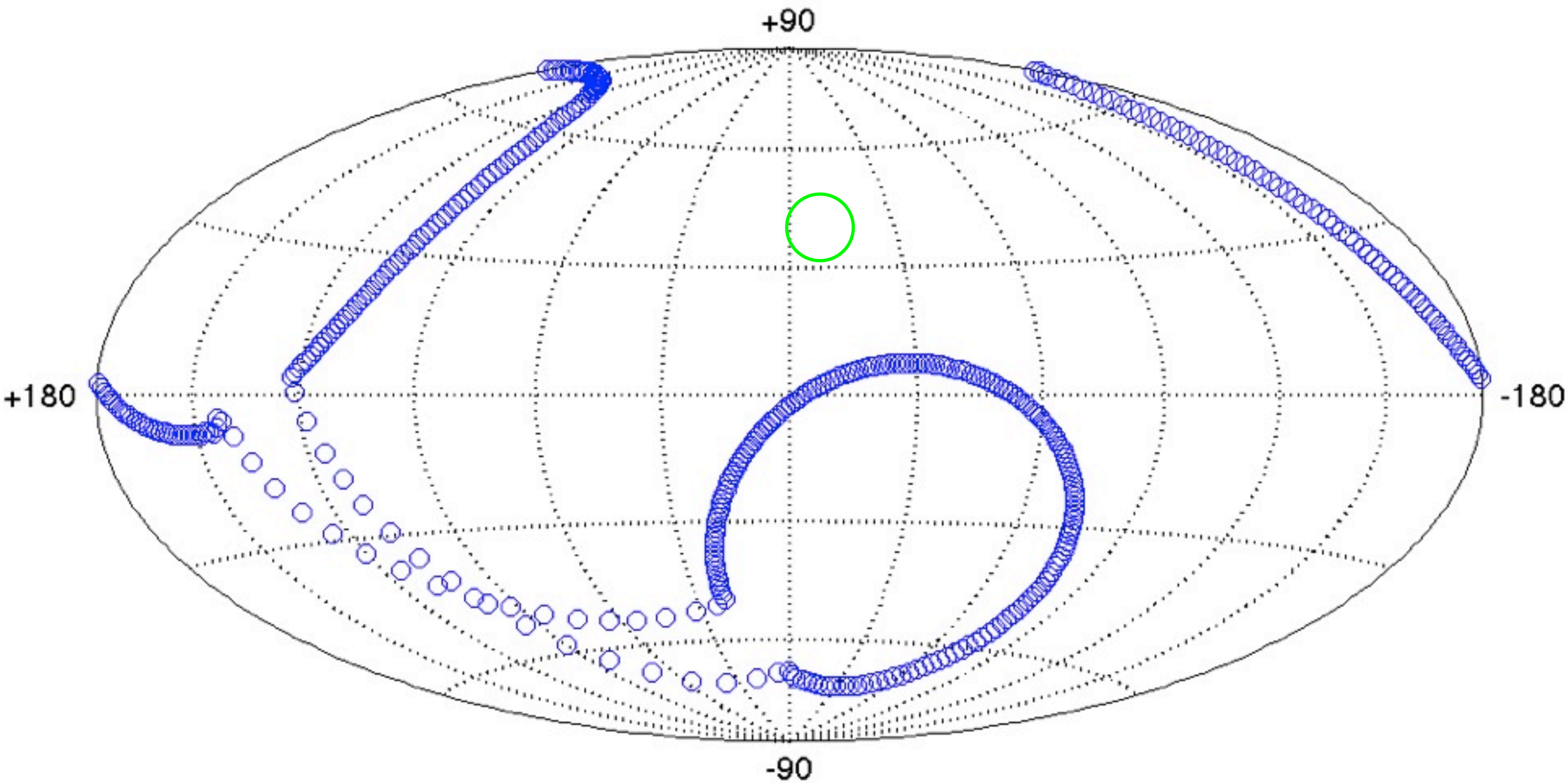

- Modeling must also account for the “observing profile”.
- Rate of γ rays from source depends on its (constantly changing) position in the field of view of the LAT.

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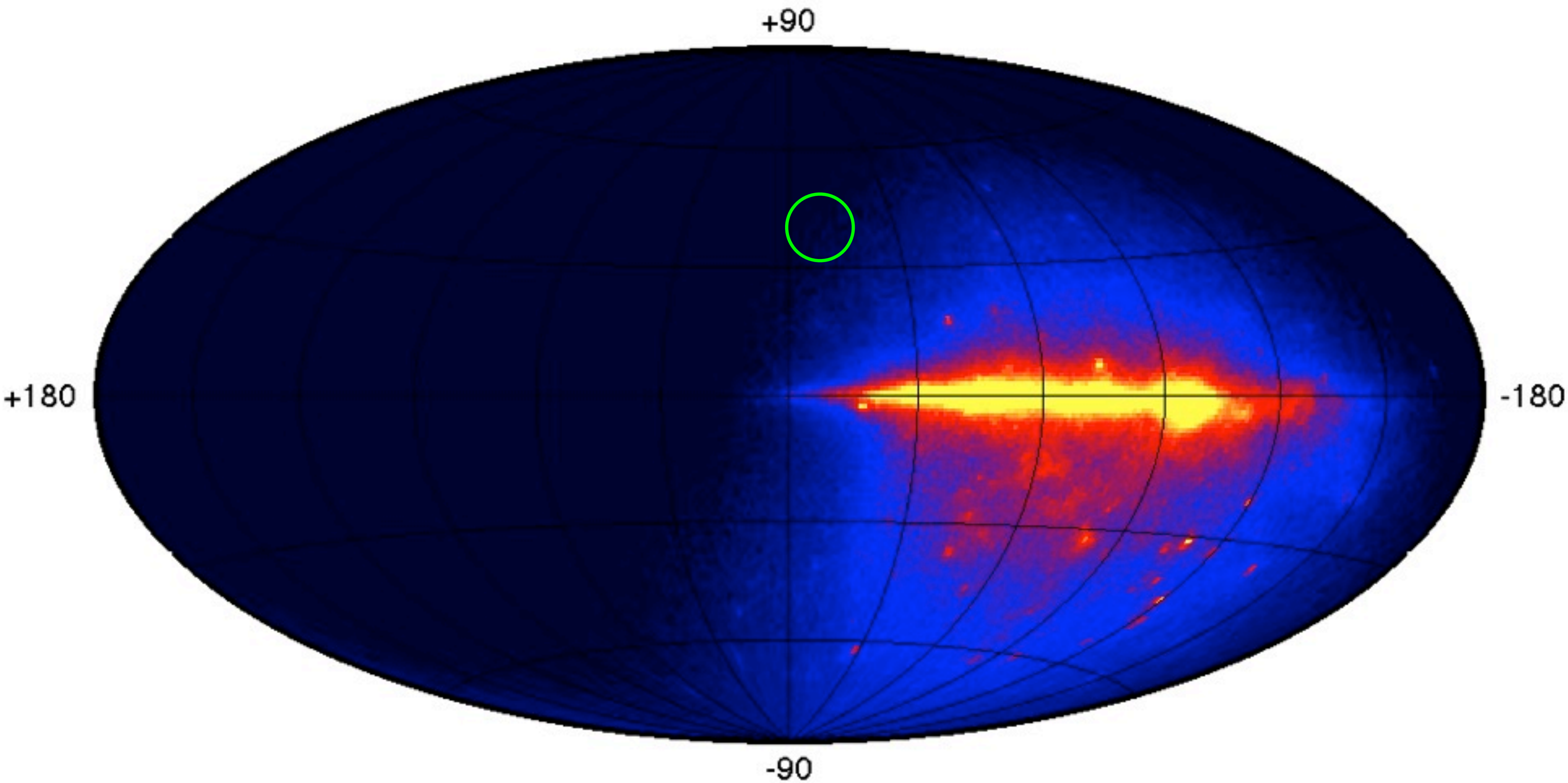

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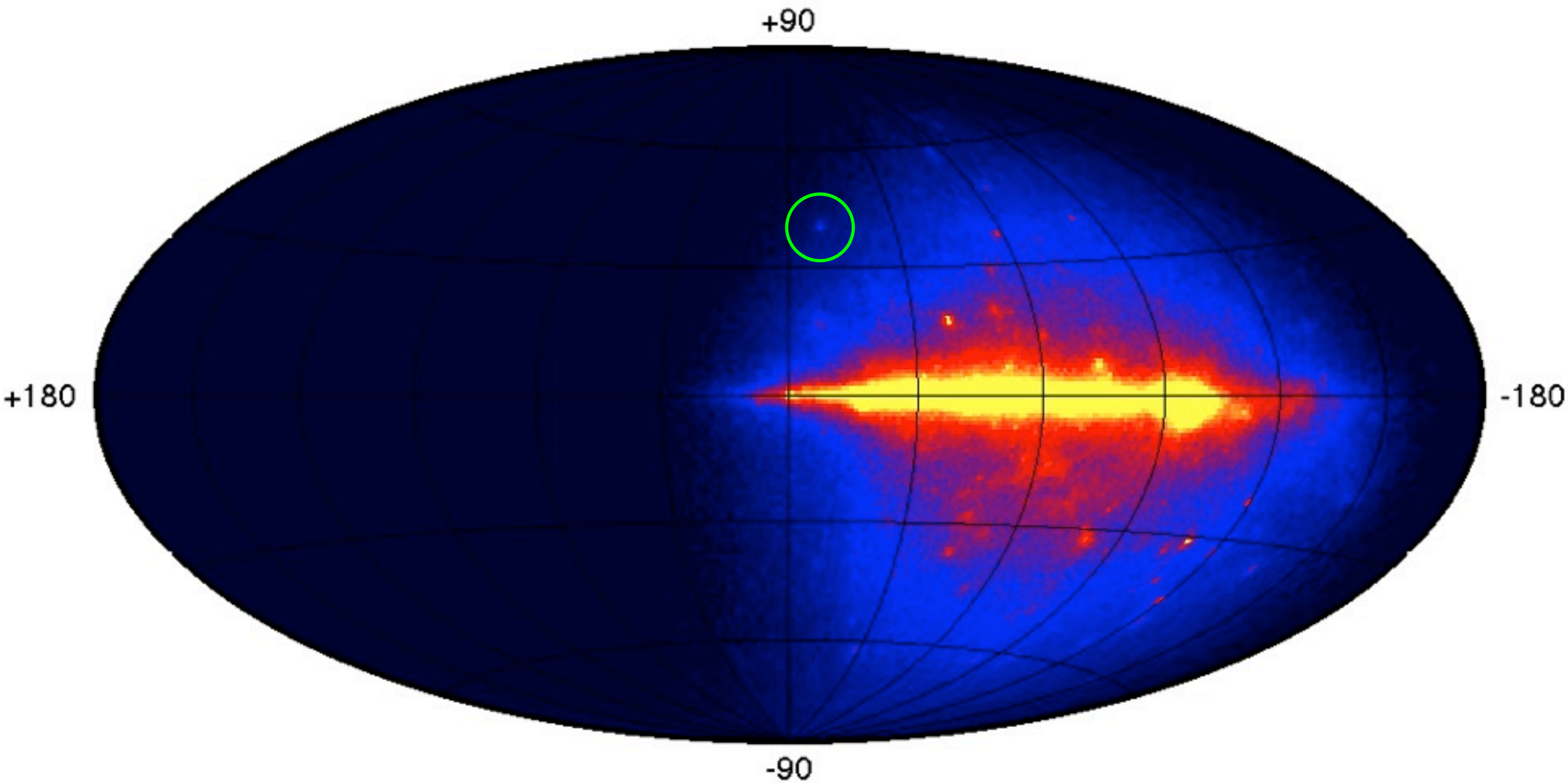

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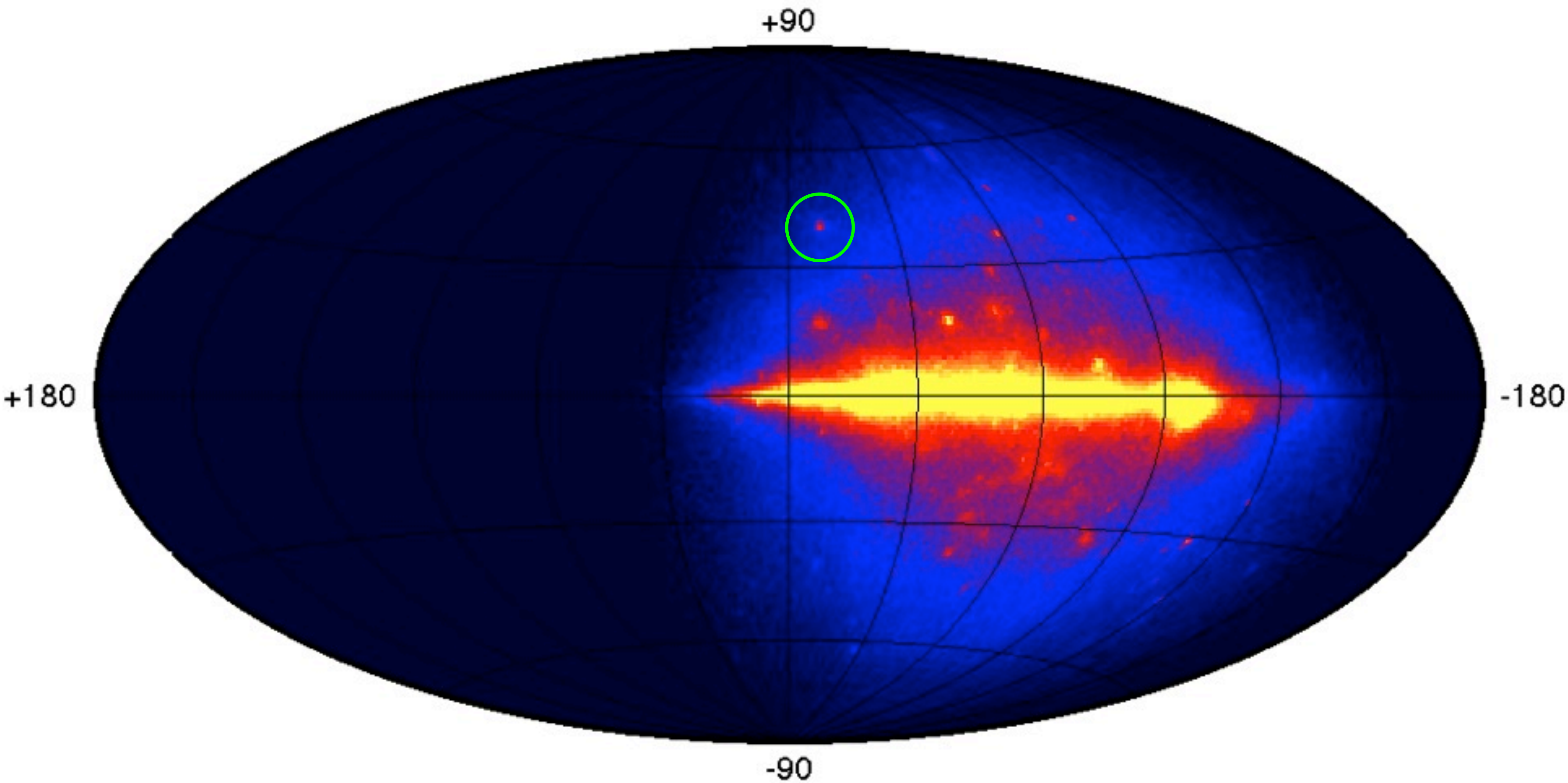

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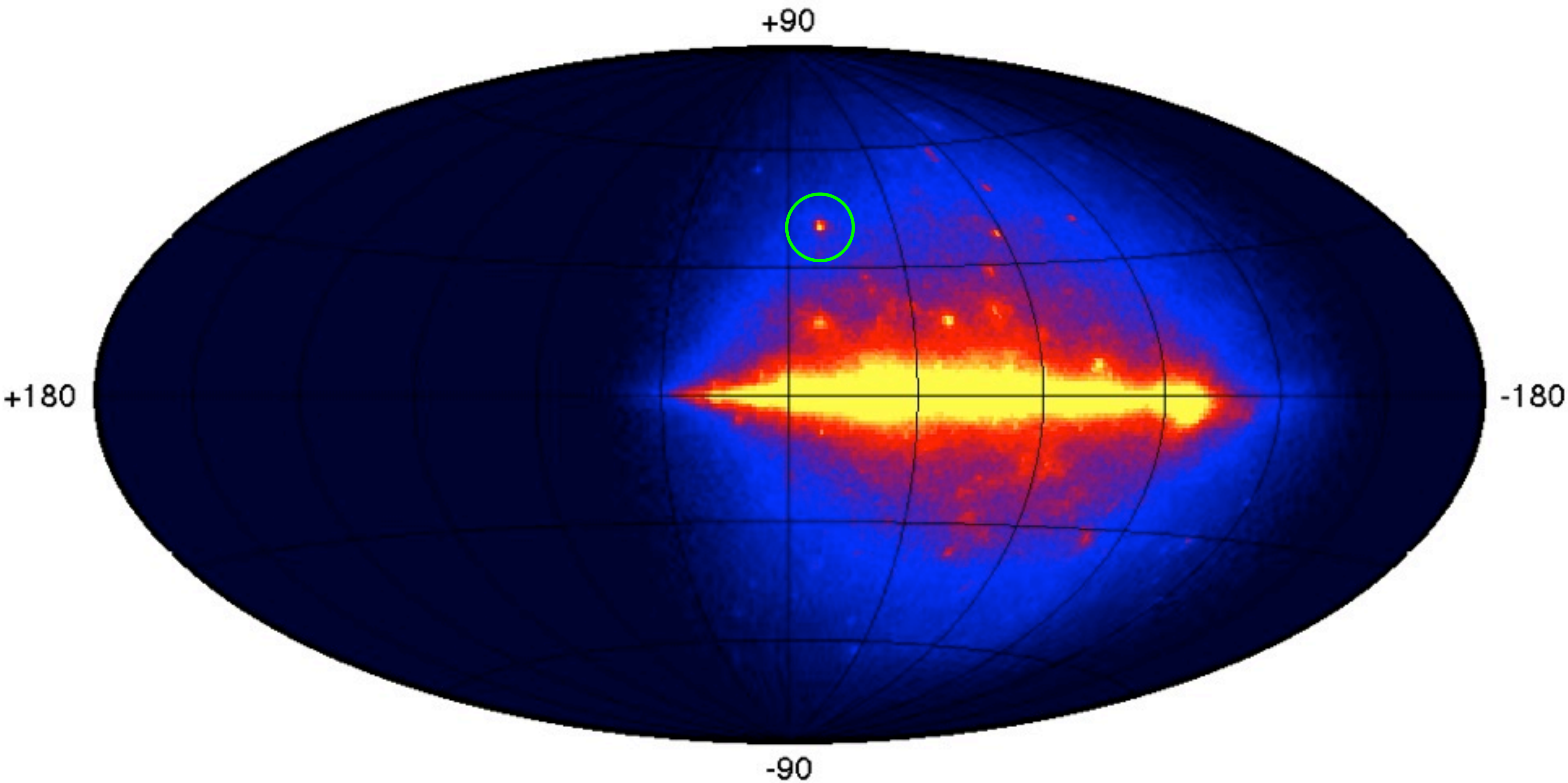

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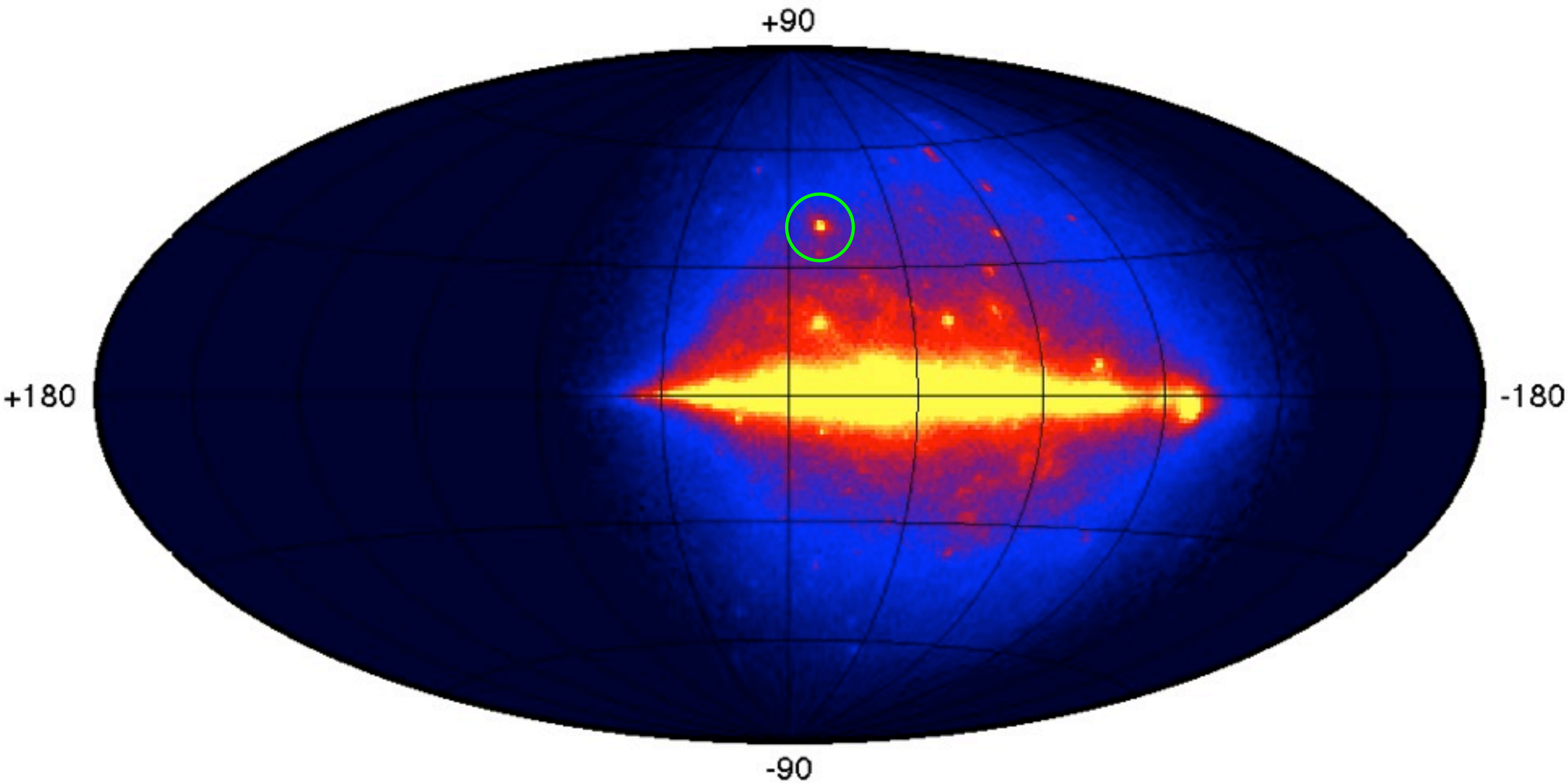

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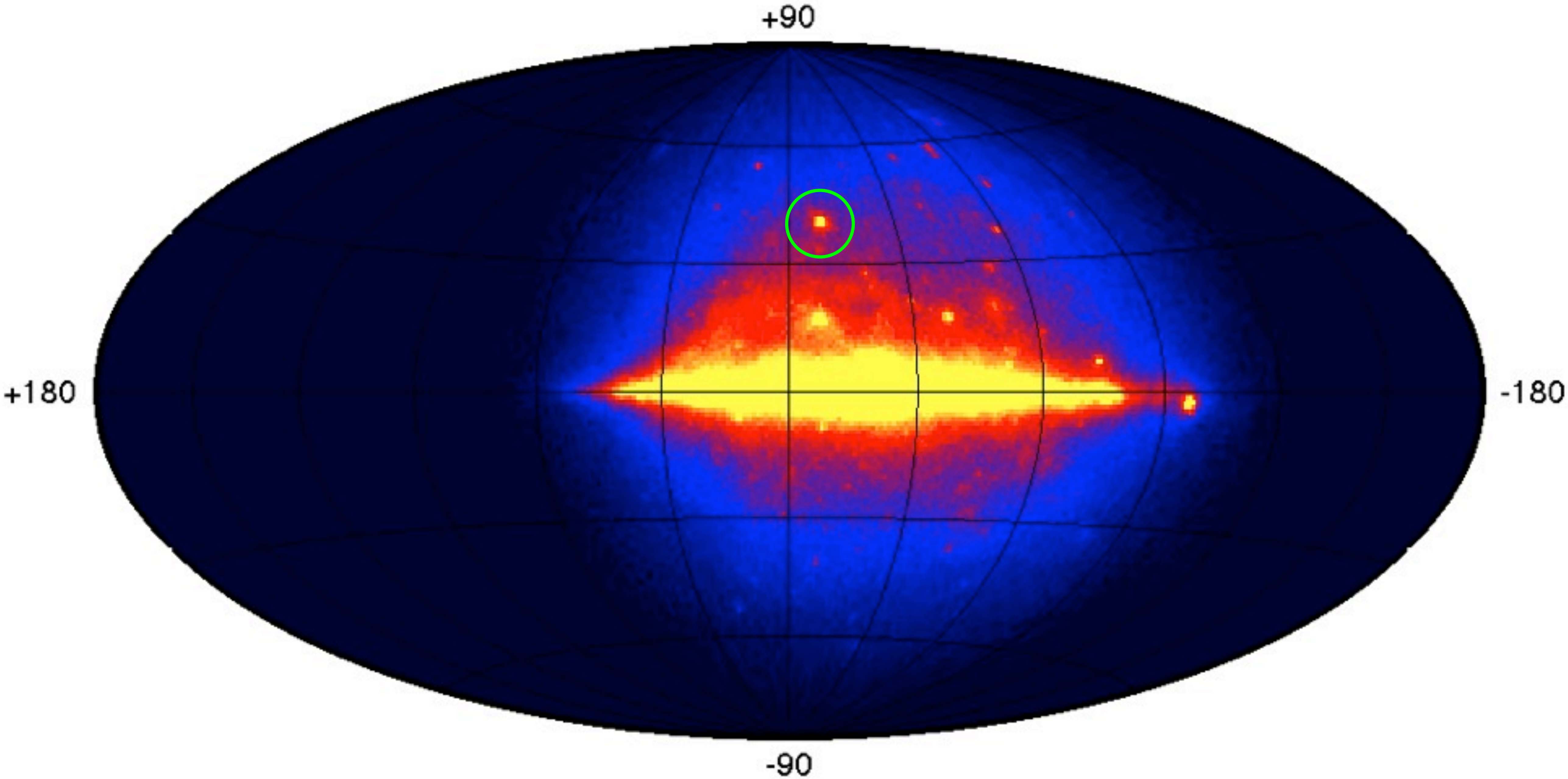

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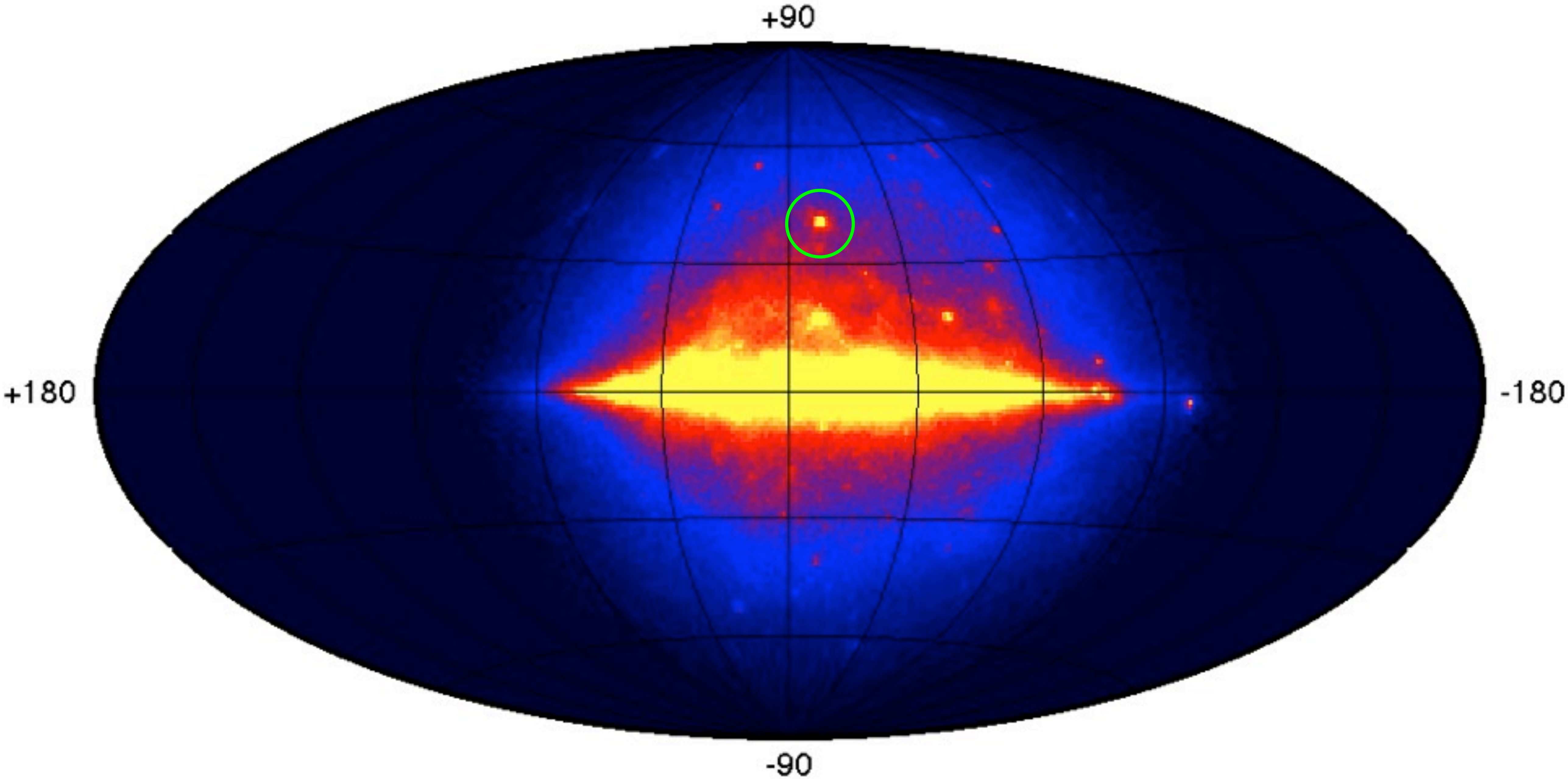

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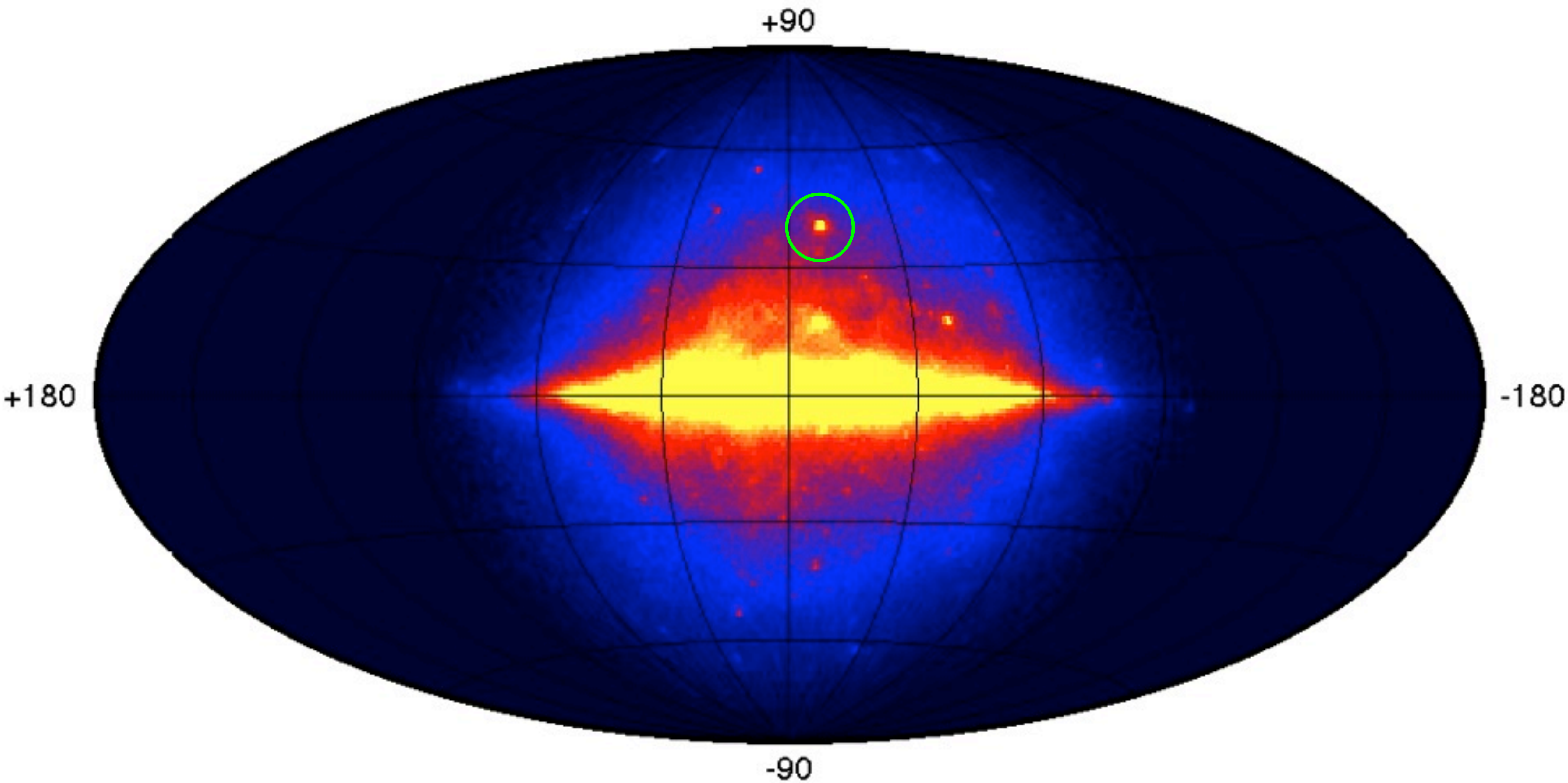

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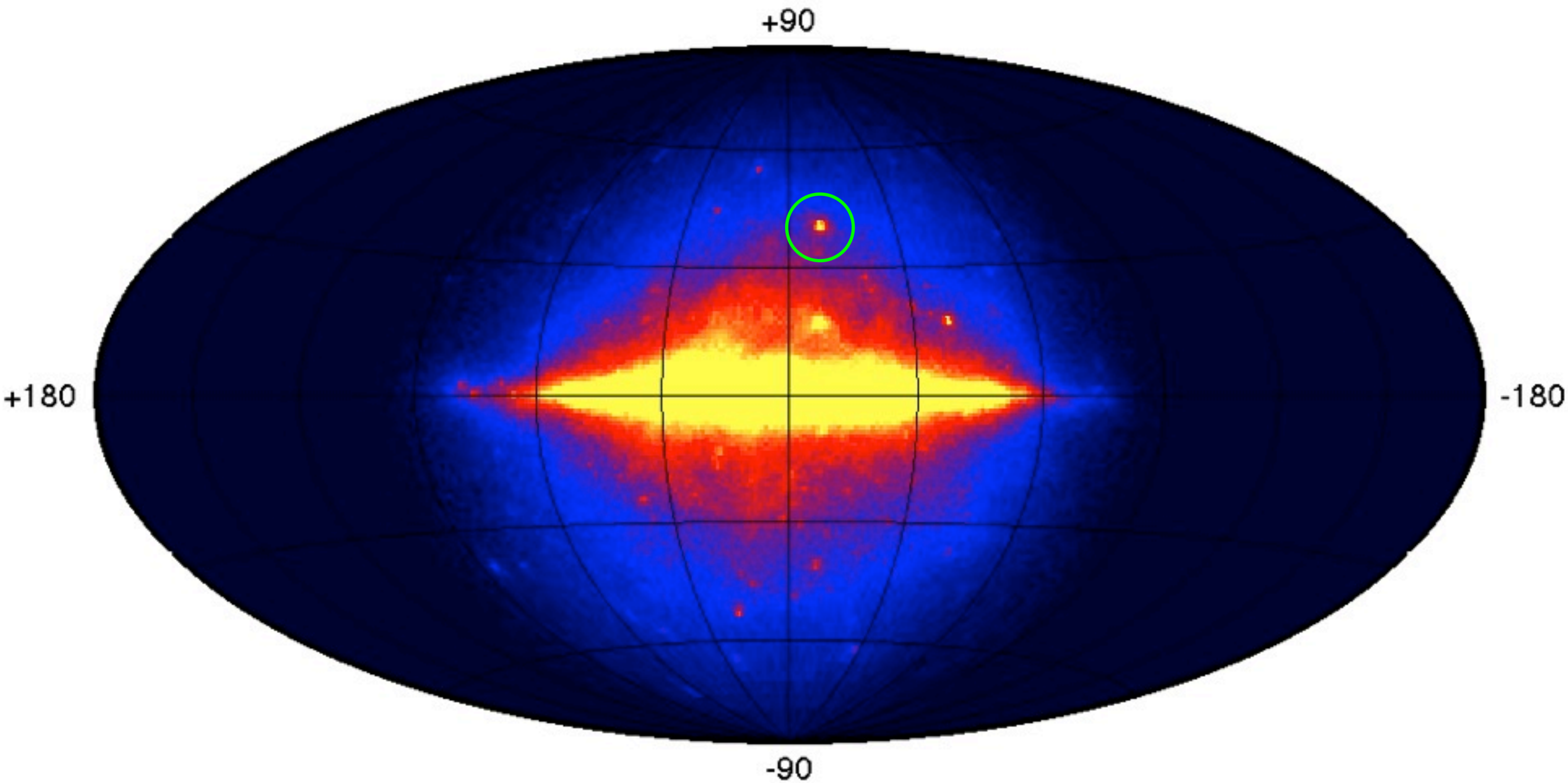

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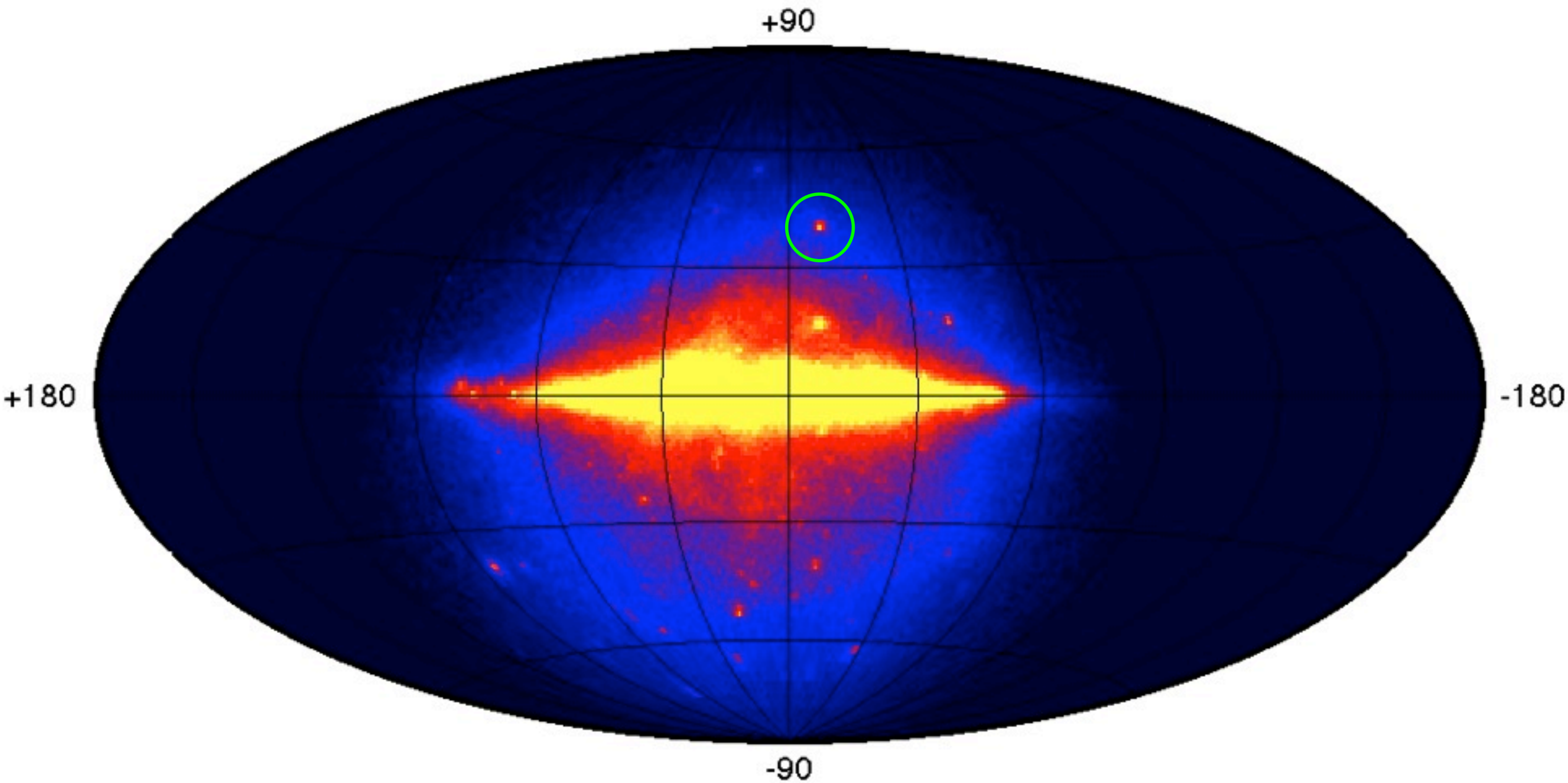

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Model

- Sky model
  - Spatial distribution of sources in ROI (point-like and extended sources)
  - Spectral model for each source
- Observational response (“exposure”)
  - Observational profile
  - Instrument response functions (IRFs)

Model

Equivalents in statistics talk:

- Sky model
  - Spatial distribution of sources in ROI (point-like and extended sources)
  - Spectral model for each source

$\{S, B\}$

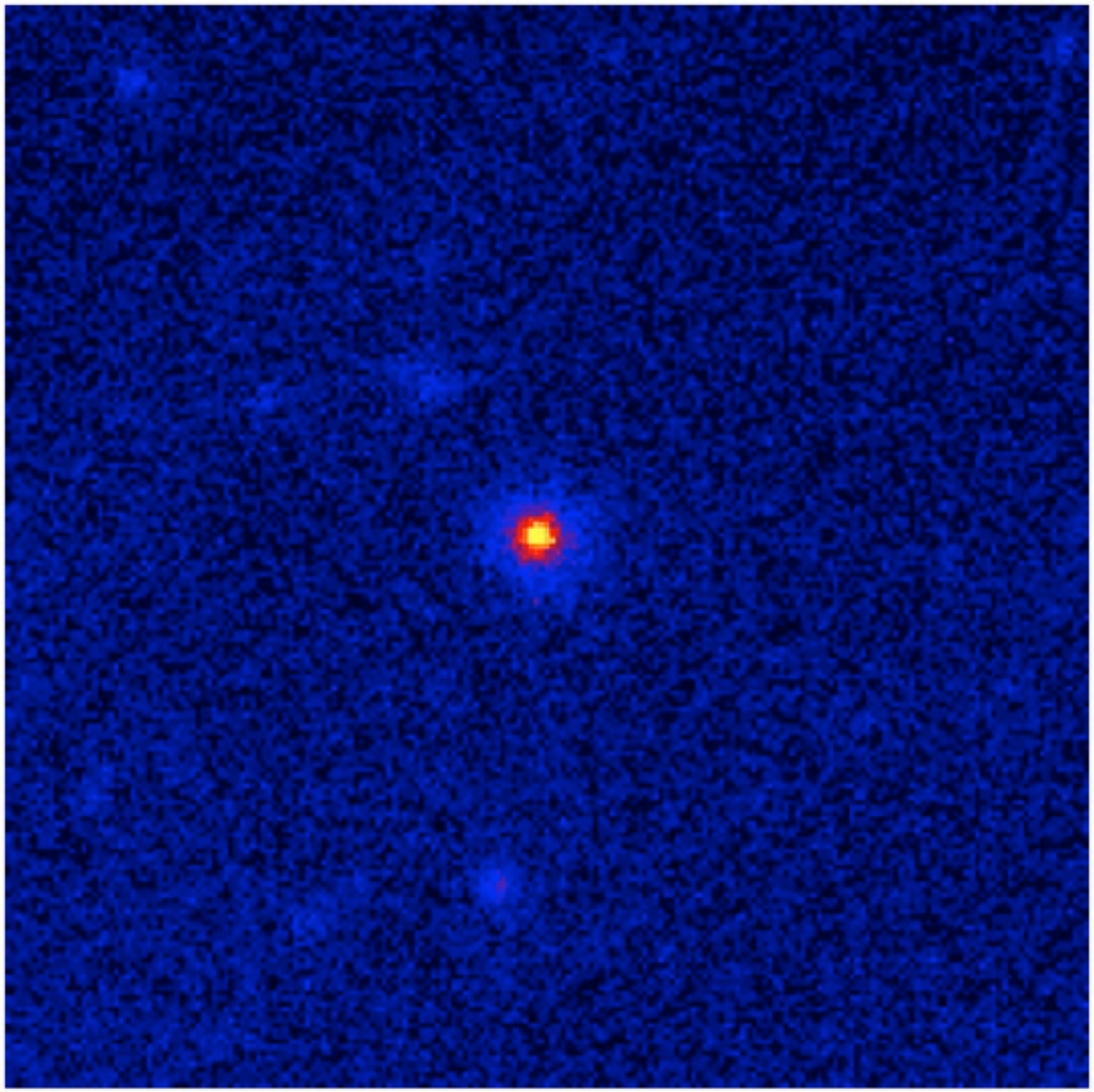
- Observational response ("exposure")
  - Observational profile
  - Instrument response functions (IRFs)

$$\begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix}$$

Sky model

- Spatial and spectral model
- Point sources (coordinates: RA & Dec)
- Extended sources (map of emission)
- Diffuse sources (full sky maps)
- Spectral types (e.g. power law - index, flux)
- No time dependence!
- All these encoded in an XML input file
  - ST and LAT catalogs can help with this task

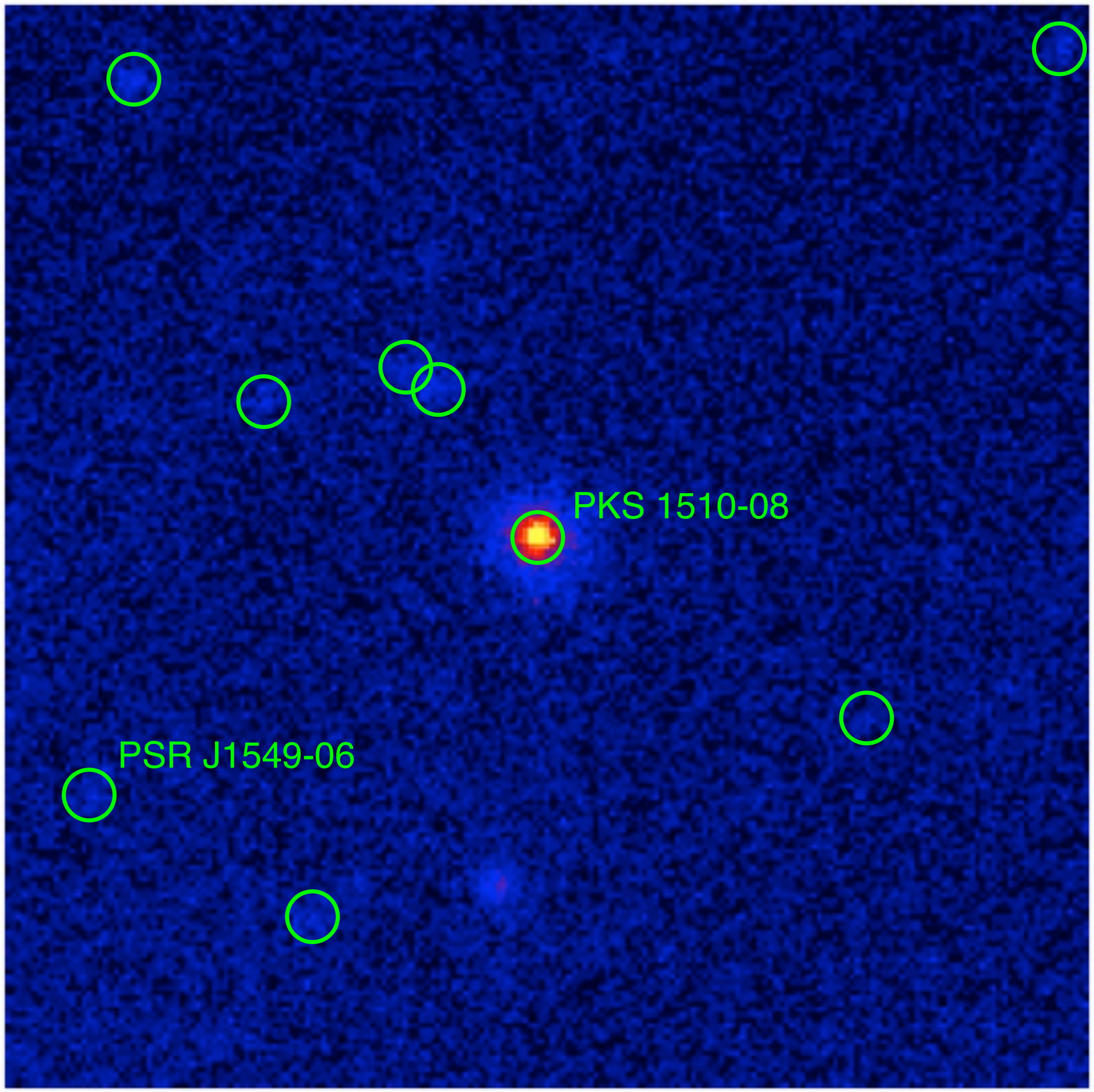
Model for our sample ROI



1GeV - 10GeV

- Sources from 2FGL catalog in (& on edge of) the ROI
  - Best-fit locations and spectral types (2yr)
- Diffuse isotropic
  - Extragalactic diffuse
  - Local cosmic rays
- Galactic diffuse
  - CR interactions
- Earth limb + sun

Model for our sample ROI



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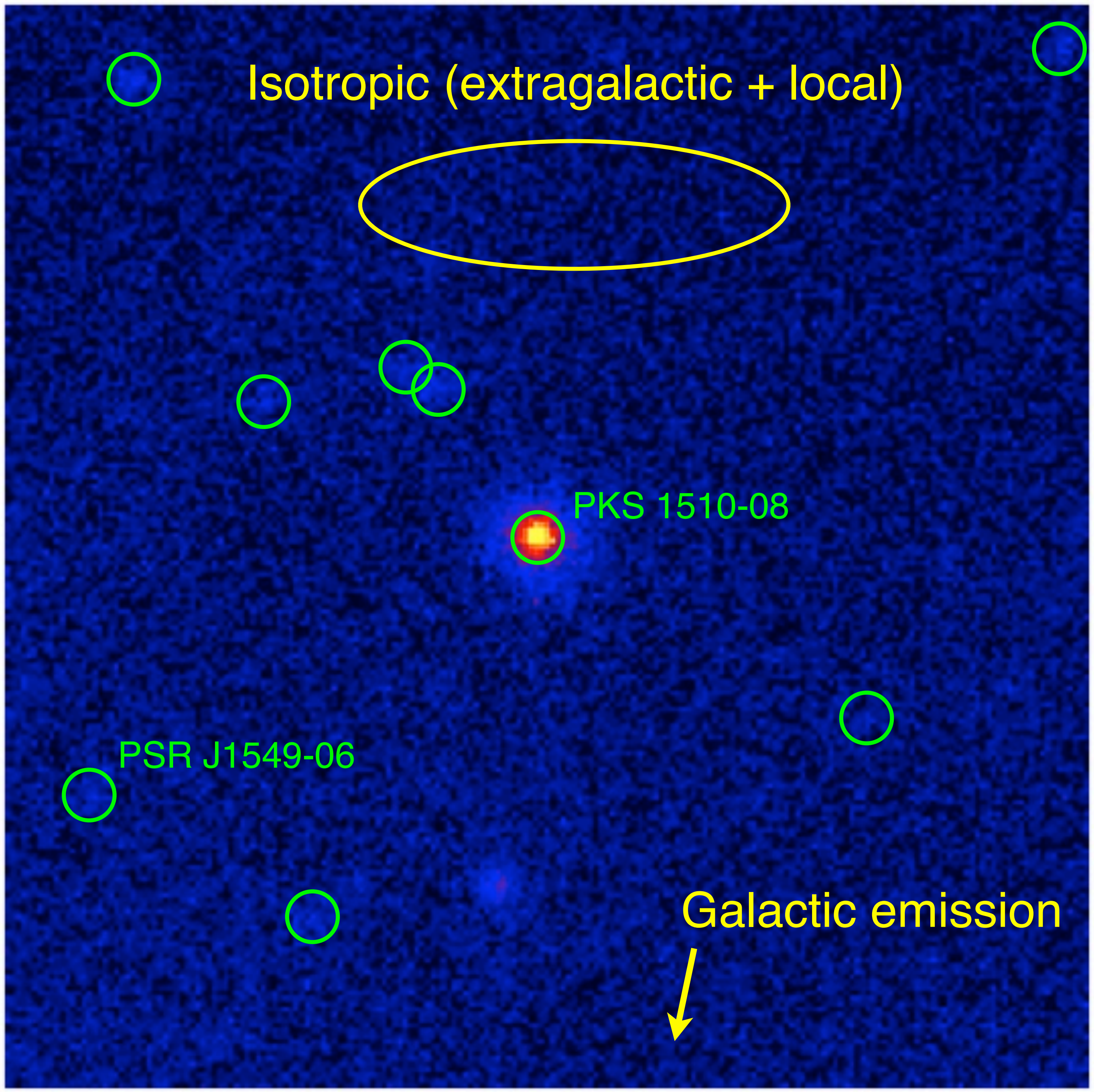

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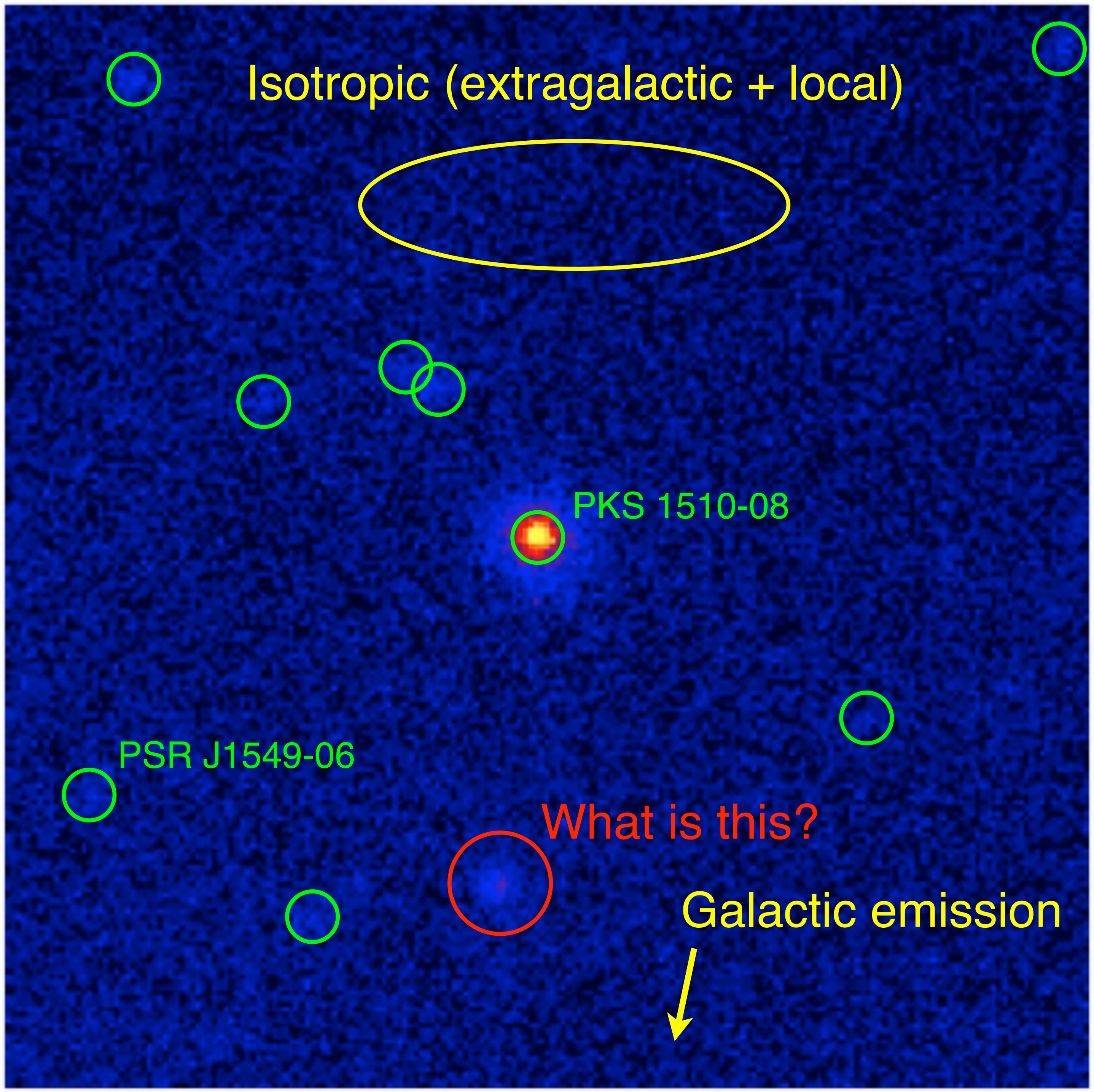

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Model for our sample ROI

$$S(E^T, \vec{p^T}|\Theta) = \sum_j s_j(E^T|\Theta_j)\delta(\vec{p^T} - \vec{p_j})$$ Point sources

$$+ S_{\mathrm{Gal}}(E^T, \vec{p^T}|\Theta_{\mathrm{Gal}})$$ Galactic diffuse

$$+ S_{\mathrm{EG}}(E^T|\Theta_{\mathrm{EG}})$$ Extragalactic + residual

$$+ \sum_k S_{\mathrm{Ext}k}(E^T, \vec{p^T}|\Theta_{\mathrm{Ext}k})$$ Other extended (optional)

$$\Theta = \{\Theta_j, \Theta_{\mathrm{Gal}}, \Theta_{\mathrm{EG}}, \Theta_{\mathrm{Ext}_k}\}$$

E.g, power law spectral model:

$$s_j^{PL}(E^T|\Theta_j) = s_j^{PL}(E^T|F_0, \Gamma, E_0) = F_0\left(\frac{E^T}{E_0}\right)^{-\Gamma}$$

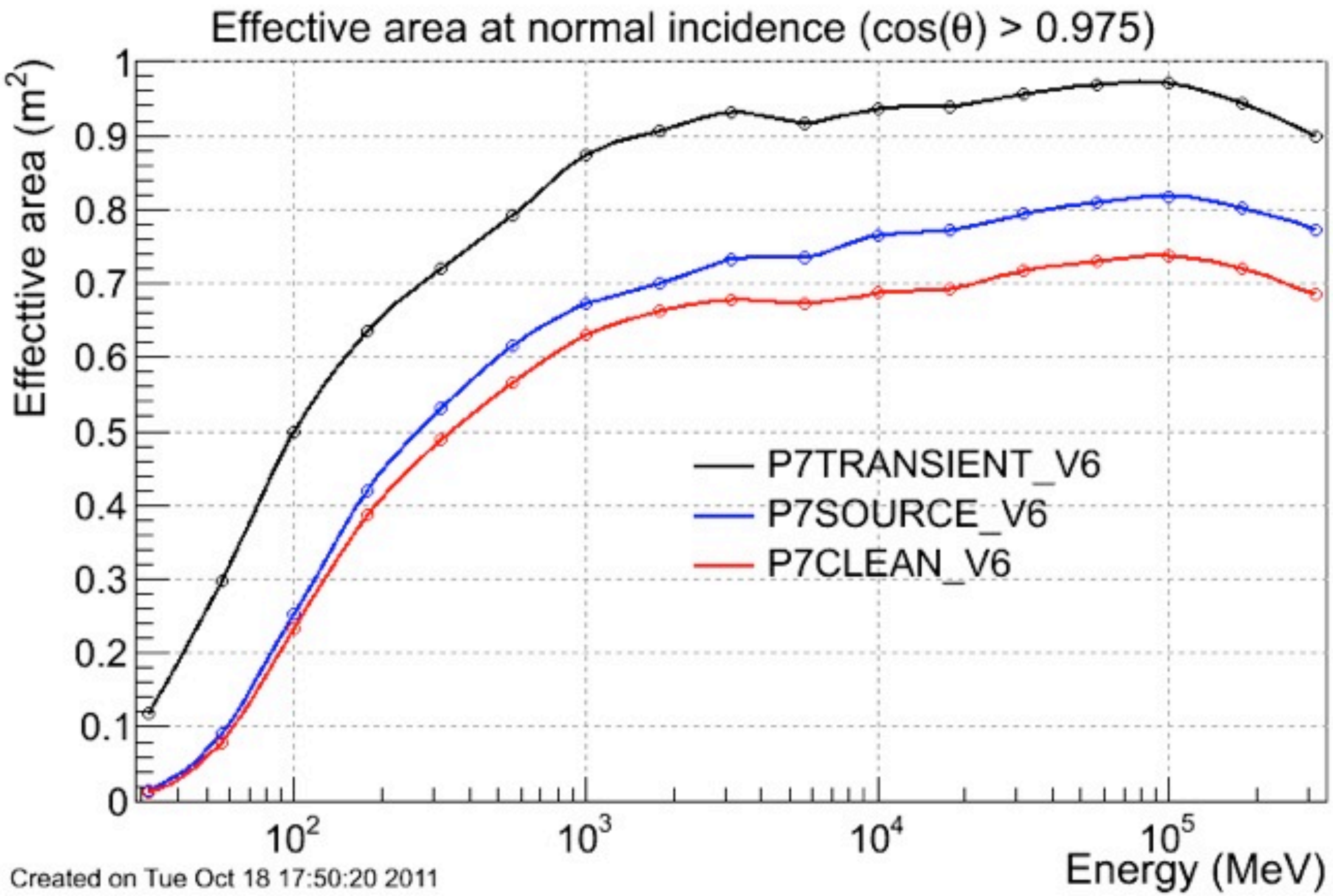
Observational profile

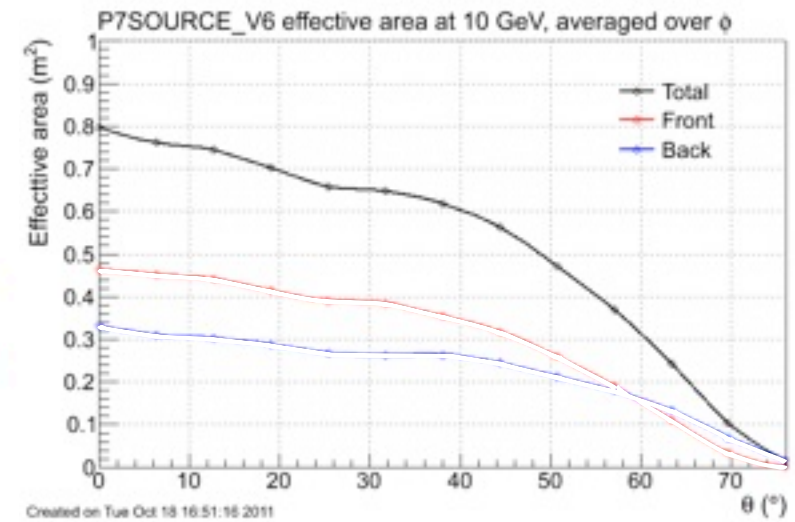
- Pointing records from FT2 file - every 30 seconds
- RA & Dec of LAT pointing direction, the z-axis
  - (and of x-axis for phi dependence)
- Observation mode - sky survey, pointed
- Jeremy described this yesterday

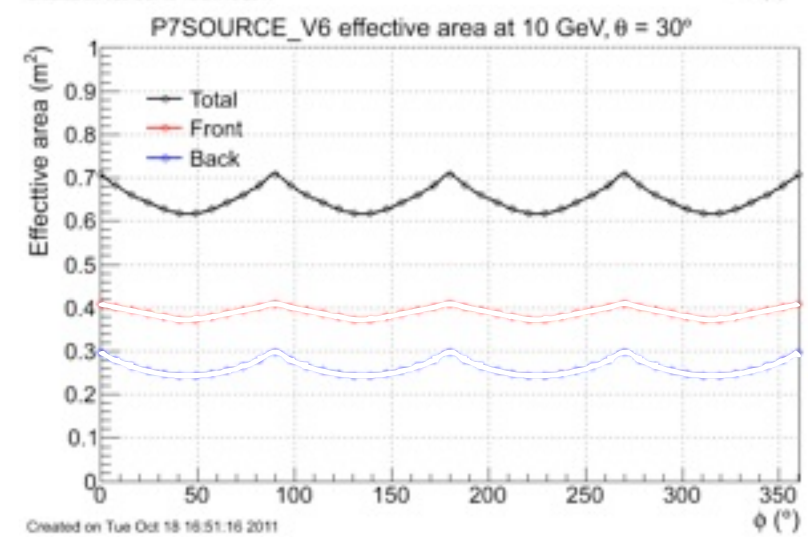
Instrument response functions

- *Effective area* - how the photon collecting area depends on energy and angle
- *PSF* - how the reconstructed photons are dispersed around their true direction in the sky
- *Energy dispersion* - how reconstructed photons are dispersed around their true energy - **often neglected in analysis**
- IRF set must complement event selection used in analysis, eg. “P7SOURCE_V6”

Effective area (EA)



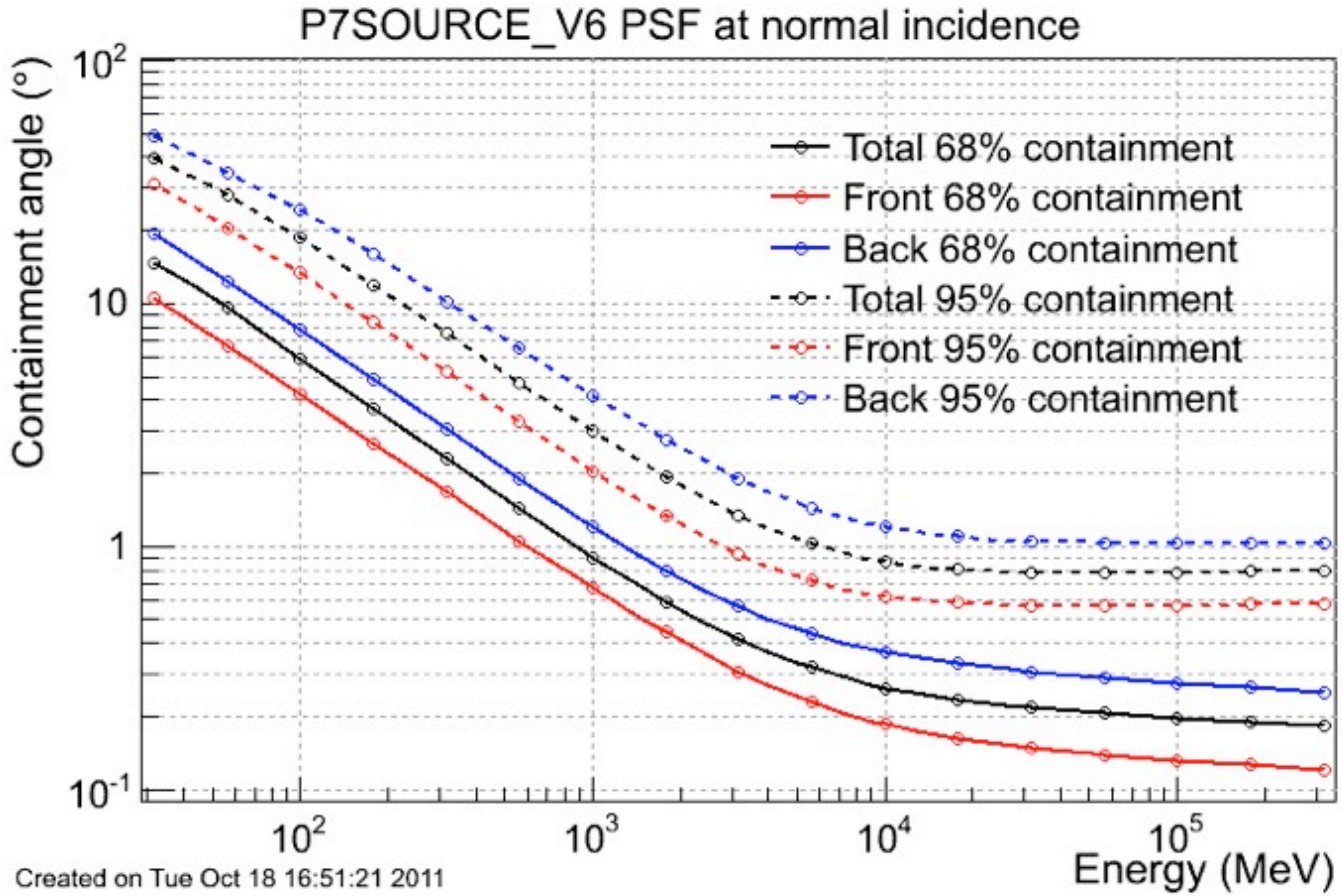




- Collecting area for events with TRUE energy E, and TRUE angles in spacecraft (θ,ϕ)

More info: http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/index.html
or: http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Point-spread function (PSF)



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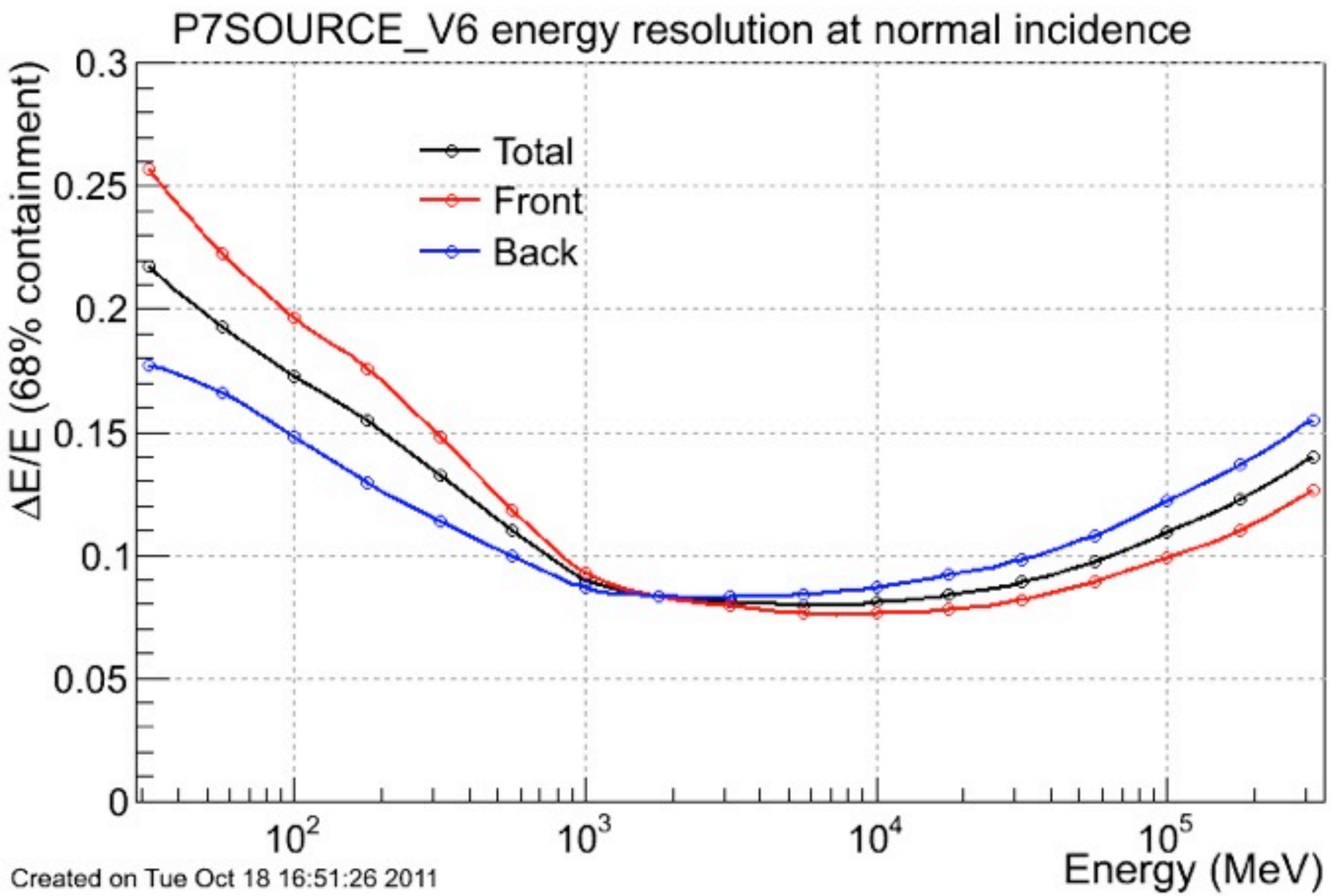
Energy dispersion (ED)



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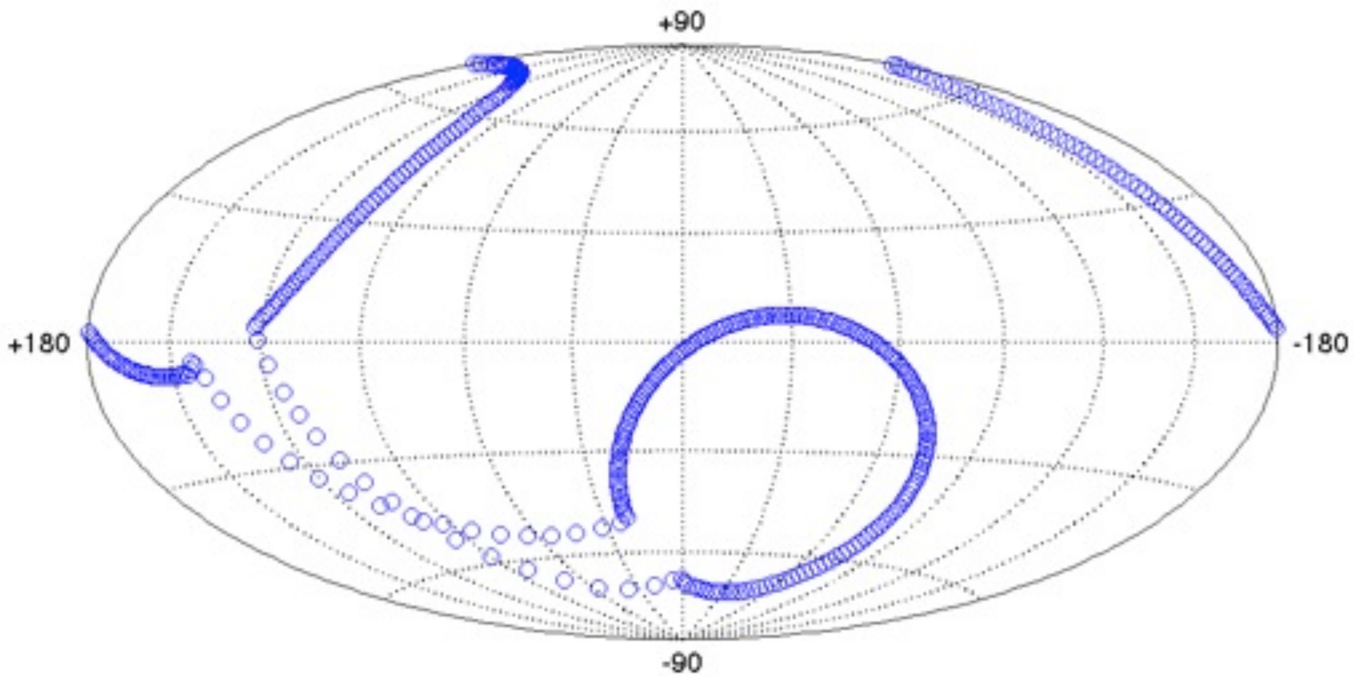
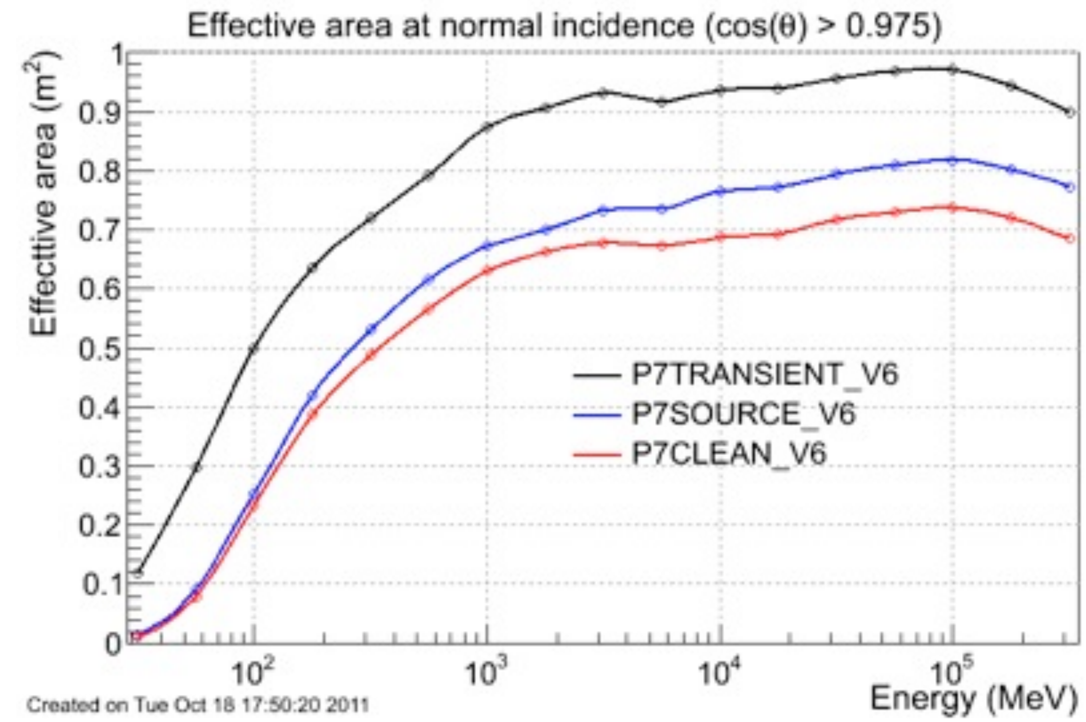
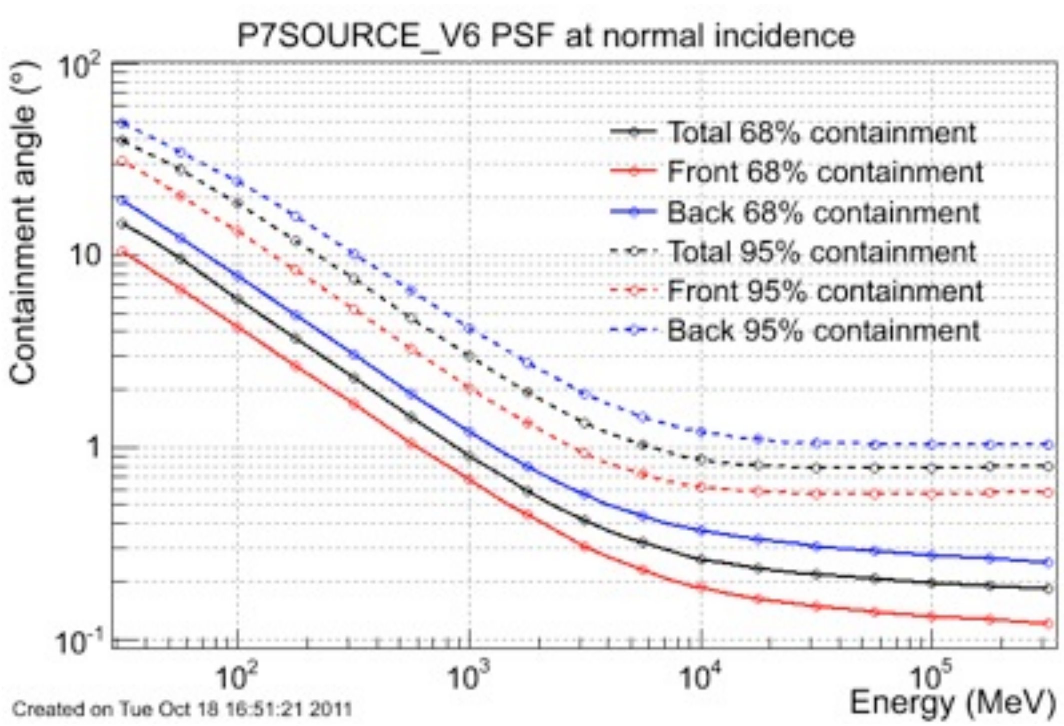
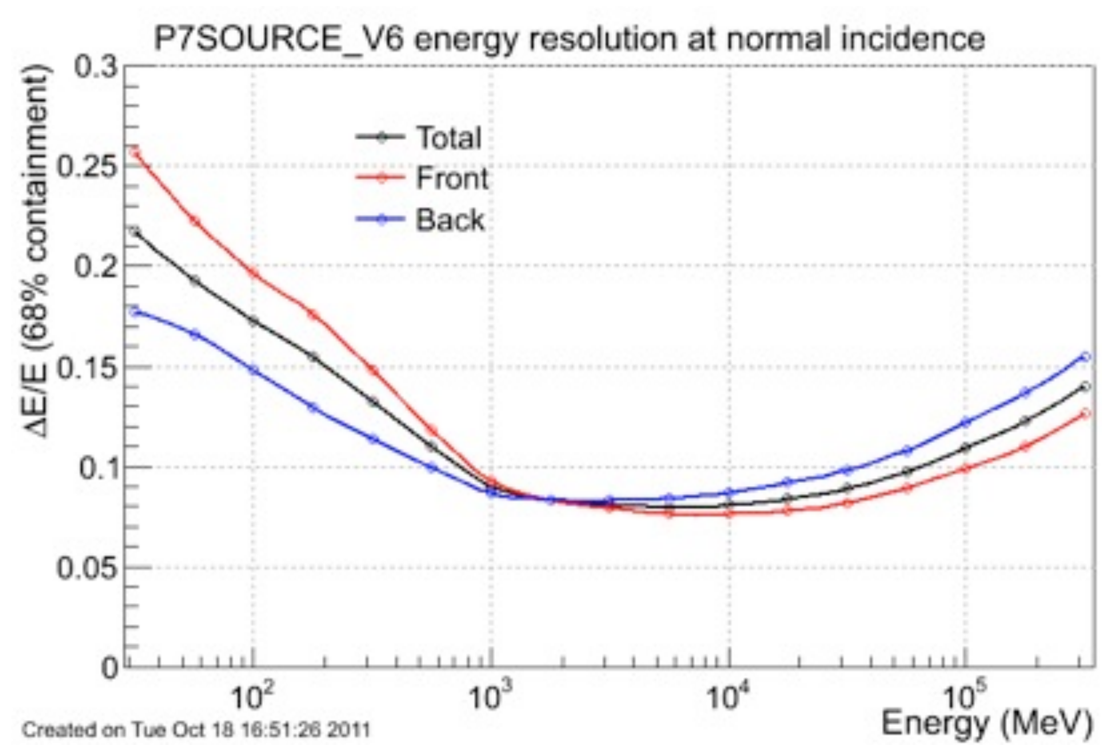
Observational response









Observational response

$$R_t(E,\vec{p},E^T,\vec{p^T},t) = A(E^T,\vec{p^T},t)$$

Effective area

Measured

True

Instantaneous response

$$\times P(\vec{p},\vec{p^T},E^T,t)$$

Point-spread function

$$\times D(E;E^T,\vec{p},\vec{p^T},t)$$

Energy dispersion

$$R(E,\vec{p};E^T,\vec{p^T}) = \int dt R_t(E,\vec{p};E^T,\vec{p^T},t)$$

Response

$$\int_0^\infty dE \int_{4\pi} d\vec{p}\, R(E,\vec{p},E^T,\vec{p^T}) = \int_{t_0}^{t_1} dt A(E^T,\vec{p^T},t)$$

$$= X(E^T,\vec{p^T})$$

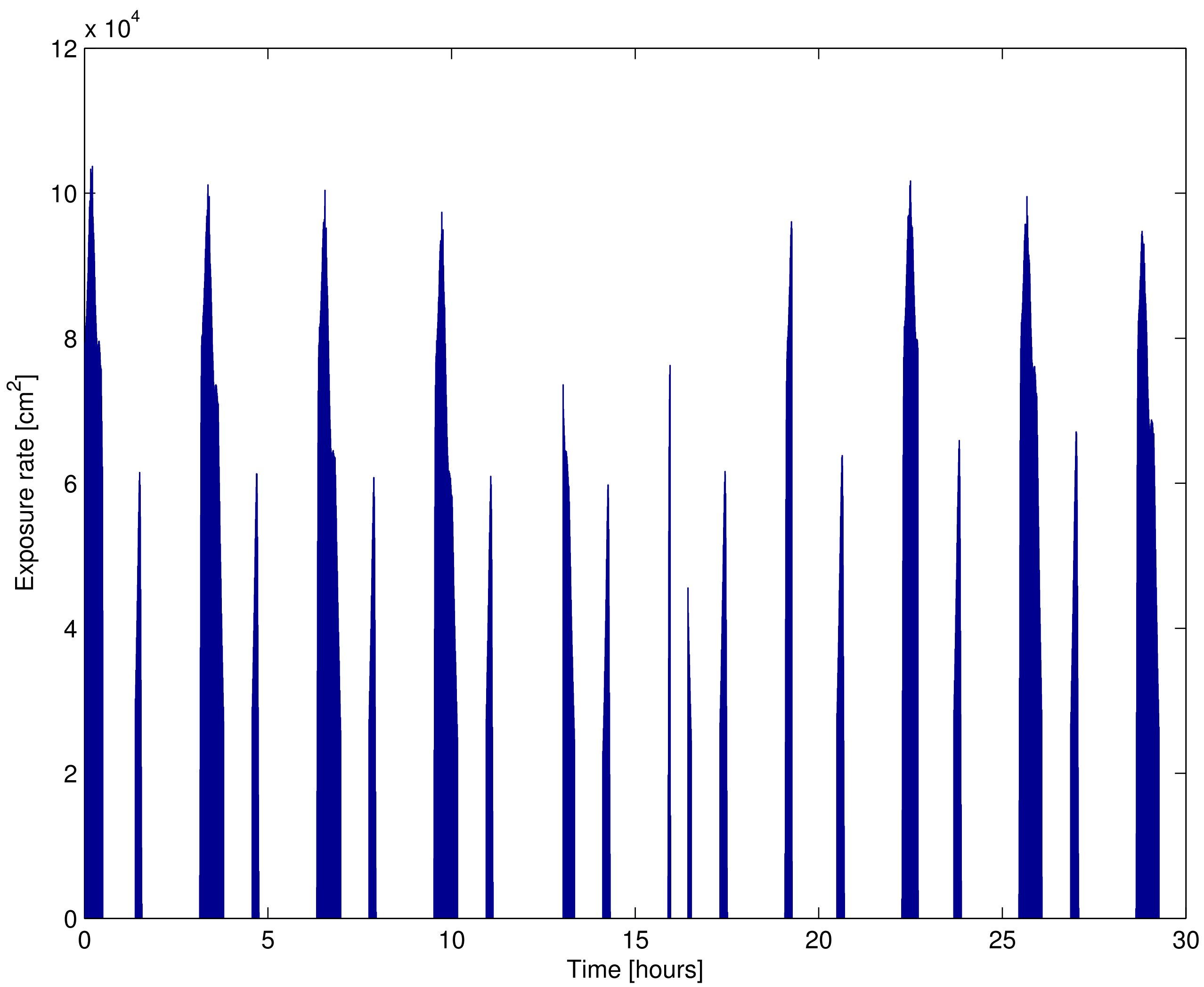
Total “exposure” - units cm²s

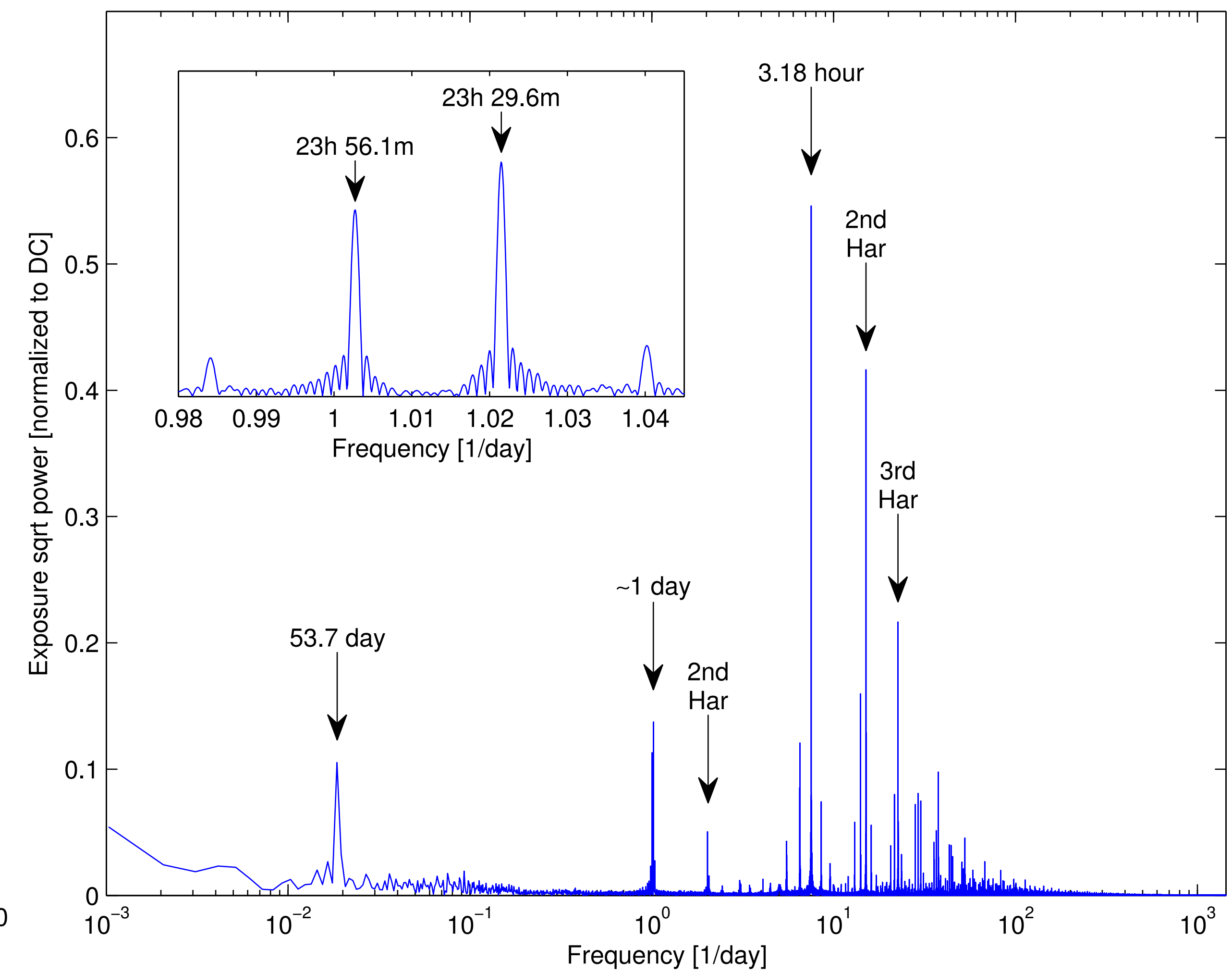
$$R(E,\vec{p},E^T,\vec{p^T})$$

Define average PSF and ED

$$= X(E^T,\vec{p^T})\bar{P}(\vec{p},\vec{p^T},E^T)\bar{D}(E,E^T,\vec{p},\vec{p^T})$$

“Exposure” versus time





- Instantaneous exposure for some source.
- Systematics may be present on short timescales or in some temporal analyses.

"Binned" likelihood function

- Events binned into channels, i, of energy and position in sky $(E_i, \vec{p}_i)$ of size $\Delta E_i \Delta \vec{p}_i$: n_i
- Log likelihood is (as in yesterday's talk):

$$\ln \mathcal{L}(\Theta) = \sum_{i \in Bins} n_i \ln \lambda_i(\Theta) - N_{pred}(\Theta)$$

- The Poisson mean for each channel is:

$$\lambda_i(\Theta) = \Delta E_i \Delta \vec{p}_i \int dE^T \int_{ROI+} d\vec{p^T} S(E^T, \vec{p^T}|\Theta) R(E_i, \vec{p}_i, E^T, \vec{p^T})$$

$$= \Delta E_i \Delta \vec{p}_i \int_{ROI+} d\vec{p^T} S(E_i, \vec{p^T}|\Theta) R(E_i, \vec{p}_i, \vec{p^T})$$

Ignoring energy dispersion

- As expected: $N_{pred} = \sum_i \lambda_i(\Theta)$

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Ignoring energy dispersion

Over region of sky larger than ROI to account for contribution of sources just outside ROI.

- As expected: $N_{pred} = \sum_i \lambda_i(\Theta)$

“Unbinned” likelihood function

- Infinitesimal channels in energy, position, time and conversion type, so $n_i \in \{0,1\}$
- The log likelihood is:

$$\ln \mathcal{L}(\Theta) = \sum_{i \in Events} \ln \lambda_i(\Theta) - N_{pred}(\Theta)$$

- Ignoring ED, the Poisson mean (density) for each channel (event) is:

$$\lambda_i(\Theta) = \int_{ROI+} d\vec{p^T} S(E_i, \vec{p^T} | \Theta) R_t(E_i, \vec{p}_i, \vec{p^T}, t_i, type_i)$$

- And: $N_{pred}(\Theta) = \sum_{type} \int dE \int_{ROI} d\vec{p} \int dt \int_{ROI+} d\vec{p^T} \int dt S(E, \vec{p^T} | \Theta) R_t(E, \vec{p}, \vec{p^T}, t, type)$

Binned or Unbinned (or both)

- Binned - *recommended by LAT collaboration*
  - Faster for long datasets (averaged IRFs)
  - Diffuse source calculation simpler
- Unbinned - *useful in certain circumstances*
  - Slow for long datasets (IRF for each event)
  - Diffuse source calculation very slow (but can be pre-calculated)
  - But higher TS values - model more accurate
- Mixed - “Composite Likelihood” (talk on Thurs)

Analysis flow - Binned

1. Create model
2. Extract data `gtselect/gtmktime`
3. Bin data into counts cube `gtbin`
4. Compute observation profile `gtltcube`
5. Compute exposure cube `gtexpcube2`
6. Produce source maps `gtsrcmaps`
7. Do MLE and compute TS `gtlike`

Analysis flow - Unbinned

1. Create model
2. Extract data `gtselect/gtmktime`
3. *Compute diffuse response* *`gtdiffrsp`*
4. Compute observation profile `gtltcube`
5. Compute diffuse exp. maps `gtexpmap`
6. Do MLE and compute TS `gtlike`

What does analysis give us?

- Estimates for all free parameters in the model (from maximizing likelihood)
- The covariance matrix (from 2nd derivative at MLEs) → Gaussian errors on parameters
- Flux and number of photons from each source
- TS for each source with a free parameter from which we get significance
- Residual counts histogram for ROI
- Convergence status

Sensitivity of LAT

From 1FGL, ApJS, 188, 405 (2010)

$$TS = 2T_0 \int_{E_{\min}}^{E_{\max}} A_{\rm eff}(E)\,dE \left(\int_0^{\pi} B(E)(1+g(\theta,E)) \times \log(1+g(\theta,E))\,d\Omega - S(E) \right)$$

$$= T_0 \int_{\log E_{\min}}^{\log E_{\max}} W(E)\,d\log E$$

$$W(E) = 2E A_{\rm eff}(E)B(E) \int_0^{\pi} (1+g(\theta,E)) \times \log(1+g(\theta,E)) - g(\theta,E)\,d\Omega.$$

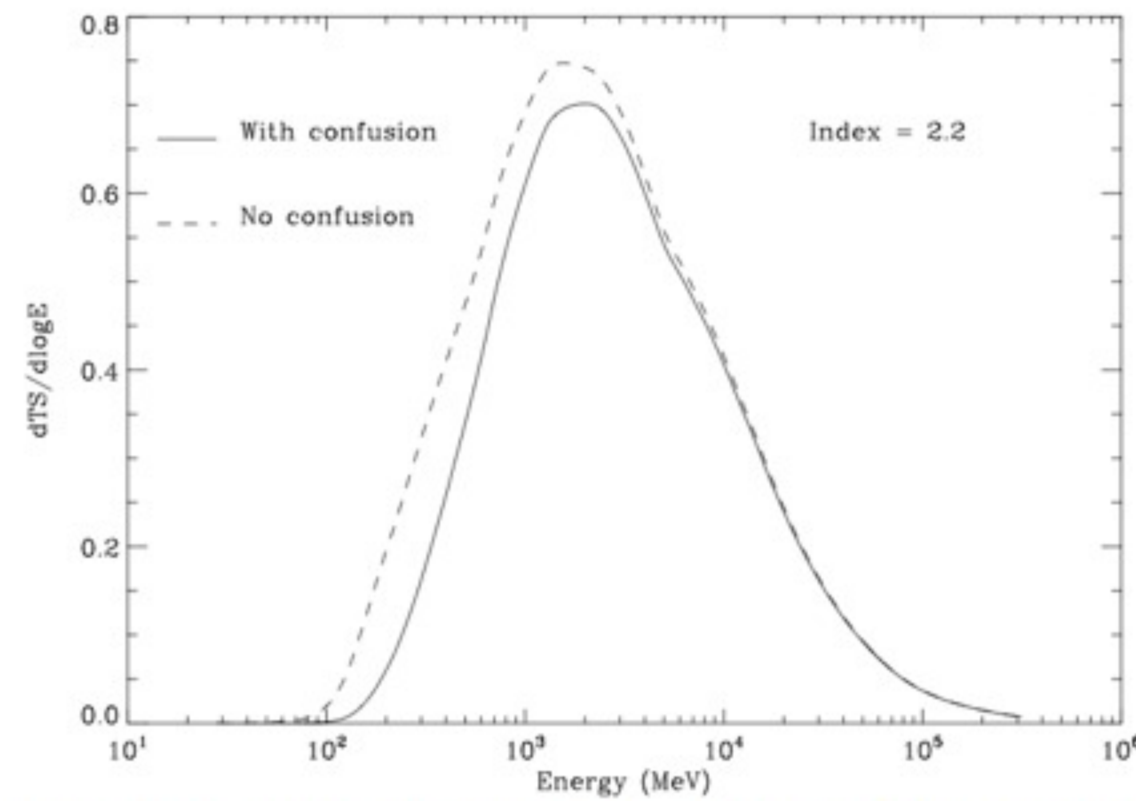
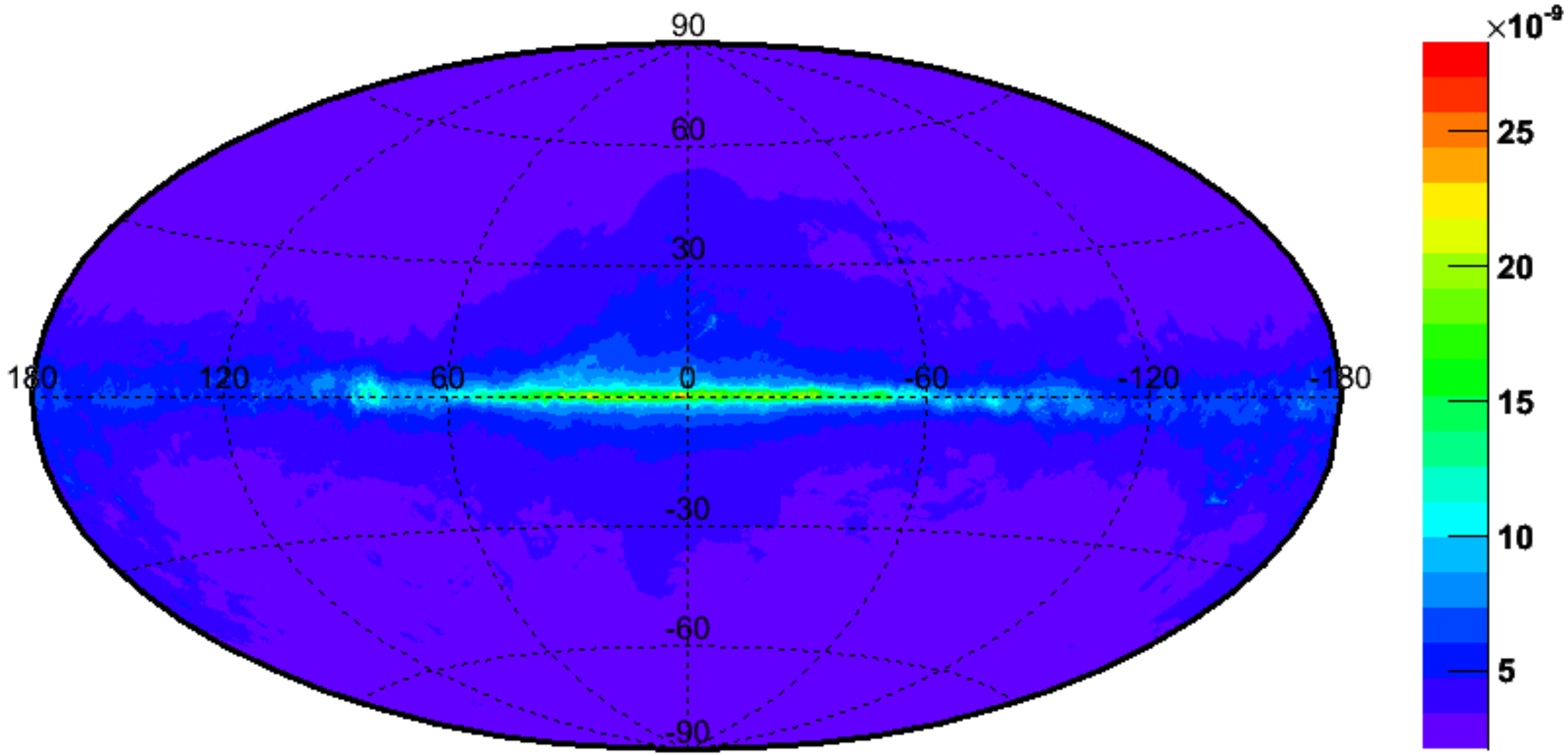


Figure 18. Theoretical contribution ($W(E)$ of Equation (A3)) to TS per Ms and per $\log(E)$ interval as a function of energy for a power-law source over the average background at $|b| > 10°$. The assumed photon spectral index is 2.2. The dashed line is for an isolated source. The full line includes approximately the effect of source confusion.

- Same kind of “no fluctuation” analysis we saw
- Plot shows how much each energy contributes to TS. Highest at 1-3 GeV as we saw by eye!

Sensitivity of LAT

From 1FGL, ApJS, 188, 405 (2010)



- Sensitivity: Minimum source flux to achieve TS=25 in 3 years with P7Source_V6 using 1FGL equations described above.